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Large Bolted Joints

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STATIC TENSION TESTS OF BOLTED JOINTS

by

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ABSTRACT

The high strength bolt, since its introduction several years ago, has been limited in use by design specifications originally drafted for the use of ordinary structural rivets.

This paper is a report of a series of tests which forms a part of a research program concerned with the use of high strength bolts in large plate splices. The prime purpose of this investigation is to examine the present design specifications which limit allowable bolt shear to a value equal to seventy-five percent of the allowable net tensile stress.

Structural specimens in the form of one-half of a butt joint were fabricated at various tension-shear ratios, bolted by a field erection crew according to the "turn-of-the-nut" procedure, and pulled to failure under static tension loads in the vicinity of 1800^k.

Test results indicate the present design practice is conservative for compact bolted joints, and seem to suggest a value for allowable bolt shear in the vicinity of one-hundred and ten percent of the allowable net tensile stress.

I. INTRODUCTION

1.1 Purpose

The rapid acceptance of the high strength bolt by the steel construction industry, combined with the lack of sufficient knowledge concerning the bolt's structural behavior, was the main reason for the development of the "substitution rule" for design. This specification permits one high strength bolt to replace one structural rivet (of the same nominal size) in structural designs. The basic properties of the parent materials of the high strength bolt and the structural rivet suggest a superiority for the bolt, but since this strength advantage has not been completely demonstrated by structural applications, the high strength bolt continues to be governed by the "one for one" specification.

Since the initial adoption of the present specifications, considerable information concerning the properties of the high strength bolt has been obtained from laboratory testing at many universities across the country; however, in the main, these investigations have been concerned with relatively small bolted connections. The testing program at Lehigh University has as the object -- "to study the behavior under static tension loads of large plate joints connected with high strength bolts to determine if fewer bolts may be used than presently required by specification." The primary interest of the program is an investigation of the ultimate, or failure, characteristics of bolted joints.

1.2 Scope

In its entirety, the "Large Bolted Joints" project at Lehigh consists of static tension tests of bolted joints using 7/8", 1", and 1 1/8" high strength bolts, with special investigations regarding butt joints, shingle type joints, joints fabricated from high strength steel, and the "unbuttoning" phenomena in long joints. Eventually, the program will include the testing of bolted joints at loads in the vicinity of 5000^k. This report is concerned with the results of the first group of tests which consists of structural plate splices fastened with 7/8" A325 bolts arranged in compact patterns. Tests of similar specimens using 1" and 1 1/8" bolts have been completed and will be reported in a later paper.

In an attempt to either substantiate the present design ruling for high strength bolts or to illustrate the conservatism of the present practice, the ratio of net tensile stress in the plate to bolt shear stress was chosen as the basic variable of the testing program. A list of the many possible variables encountered in a program of this nature is given in Table 1 with comments concerning the variables included in this investigation.

In all, the tests related to the 7/8" bolts, or "B Series" as they are designated, (outlined in Table 2) include six bolted joints at various tension-shear ratios and one comparison riveted joint. Being designed to fail at load in the vicinity of 1800^k, the test specimens might be called full scale structural joints. Information concerning bolting procedure, bolt tension, slip, joint elongation, and plate strains within the bolt pattern has been recorded.

1.3 Review of Literature

Of the many papers found in the literature related to the use of high strength bolts, the following selections have been found to be most closely related to the work reported in this paper.

Static (and fatigue) tests of bolted joints having varied tension-shear ratios were reported by Munse, Wright, and Newmark(1) in 1954. Tests of 2 and 3 bolt, butt and lap joints using 7/8" bolts resulted in no shear failures in 12 tests with T/S = 1.00/0.75; one shear failure in 12 tests with T/S = 1.00/1.00; and ten shear failures in 16 tests with T/S = 1.00/1.25.

In 1954, comparisons of riveted and bolted joints were made by Baron and Larson(2) for double butt and double lap joints, 9 1/2" wide, using 3/4" fasteners in 4 and 6 fastener patterns with a T/S of 1.00/0.75. Bolts which were tightened by a torque criterion of 280 ft-lb (produced low clamping according to present practice) slipped into bearing at a nominal shear stress of 9 to 16 ksi. Hot driven and cold driven rivets were used in the comparison joints, and slipped at approximately the same load level. Experimental plate efficiencies were greater than the theoretical values for joints having drilled holes.

Other comparisons of riveted and bolted connections were given by Carter, McCalley, and Wyly(3) in their tests of WF bridge hangers tested in tension. SR-4 gages were used on the bolt shanks to obtain clamping force. No slip occurred below axial design stresses. Bolt clamping force decreased when the WF reached the elastic limit.

In 1954, Hechtman[4] investigated slip in double lap joints using 1" bolts in 1" butt plates with 1/2" lap plates (4, 6, and 8 bolts). Major slip occurred at a shear of 20 ksi on the gross area of the bolts, but additional slipping was noted before the bolts were in full bearing. Earlier slips at increased T/S ratios were attributed to loss of bolt tension due to the Poisson effect on the plates. A nominal coefficient of friction equal to 0.34 was reported.

In 1957, a statistical study of other investigations involving a change in the T/S ratio and the effect on slip and the coefficient of friction was given by Vasishth, Lu, and Vasarhelyi[5]. Increases in the T/S ratio seemed to promote early slip.

In 1954, Schenker, Salmon, and Johnston[6] in their report on connections, discussed elongation of bolted joints and mentioned that total elongation, before slip occurs, may be approximately equal to the elongation of a solid bar ($\Delta \simeq PL/AE$) using gross area for the value of "A". Referring to the doctoral dissertation by F. W. Shutz, the authors discussed the theory of plate efficiencies, and pointed out that for low values of "g/d" (gage/hole diameter) in the range of values from 8 to 2, net efficiencies may be greater than 100%.

An investigation of the use of high strength bolts in structural connections was reported by Munse[7] in 1956. Small double lap joints (4 - 7/8" bolts) and connections of gusset plates bolted (14 - 7/8" bolts) to the flanges of "I" sections were tested. Slip loads occurred at values greater than working loads.

Tightening procedures for high strength bolts have produced considerable literature. Drew[8] writes of procedures for tightening; Frincke[9] outlines the "turn- of-the-nut" method used by Bethlehem Steel Company; and Zar[10] notes cases of under-torqued bolts, and presents a procedure for tightening and inspecting.

Static tension tests of large bolted joints were reported by Lu, Vasishth, and Vasarhelyi[11] in 1957. Two specimens, one using 27 bolts in a long, "open" pattern with a T/S of 1.00/0.80, and one using 30 bolts in a compact pattern with a T/S of 1.00/0.71 were tested to failure. Two 80 bolt joints were examined for slip characteristics, but not ruptured since the strength of the specimens exceeded that of the testing machine. Failure of the compact 30 bolt joint consisted of plate tearing through the net section; while failure of the long 27 bolt joint consisted of bolt shear marked by preliminary corner bolt failure at a nominal shear of approximately 53 ksi. A friction coefficient of approximately 0.22 was reported for the 80 bolt joints. The authors mentioned that lower values for coefficient of friction were obtained when using the "one-turn-of-the-nut" method as compared with values obtained using the minimum bolt tension criterion for tightening bolts; however, the higher clamping force produced by the former procedure resulted in higher values of slip load.

Tension tests of large riveted joints were reported in 1939 by Davis, Woodruff, and Davis[12]. The information obtained in these tests seems applicable to bolted joints. Premature fastener failures in joints using ductile plates, slip characteristics dependent on pattern, and optimum values of pitch and gage were reported.

Summarizing, it seems that the majority of the investigations related to the testing of high strength bolts in structural joints have considered mainly small test specimens, with the exception of the tests at The University of Washington(11). Additional information regarding the effect of changing the tension-shear ratio in large joints is necessary before a change of specifications may be considered.

II. DESCRIPTION OF TEST JOINTS

The "B Series" of specimens, consisting of six bolted joints using 7/8" high strength bolts, and one comparison riveted joint using 7/8" structural rivets, is shown in Table 2. Basically, the specimens were fabricated as half of a butt joint or what might be called a "double lap" joint, consisting of an inner or main plate made up of two pieces of 18" x 1" x 7'-1" steel plate and two outer or lap plates which were each 18" x 1" x 7'-1" steel plate. Plate of constant thickness was used in order to eliminate as much as possible any variation in material properties. In order to make efficient use of the available material, only three joints were fabricated at first while the remaining material was held in storage pending the results of testing the first three.

The first three joints (B1, B2, B3) were designed on the basis of a progressively increasing T/S ratio, beginning with the present specification relation of T/S = 1.00/0.75. On that basis, Joint B1 required 30 bolts for a T/S of 1.00/0.74. It was decided to use a pattern of five longitudinal lines at a gage of 3 5/8" and six transverse rows at a pitch of 3 1/2". These dimensions produced a compact bolt group and permitted easy variation of the T/S ratio with out major pattern changes. Joint B2 was similar to B1, but omitted one transverse row of bolts so that there were only 25 bolts used, thus increasing the T/S ratio to 1.00/0.89. Similarly, Joint B3 omitted still another transverse row of bolts to obtain a pattern of 20 bolts with a T/S of 1.00/1.11.

The test results of the first three specimens provided the basis for designing joints B4, B5, B6 and BR2. It was decided to explore further in the region of T/S = 1.00/1.00. Joint B4 was designed for a T/S of 1.00/0.97 by omitting two bolts from the middle row of a 5 x 5 pattern similar to that of B2. The modification of the original close pattern for B4 lead to the design of B5 which used a still more "open" pattern, but reverted to the same T/S as in B3 (1.00/1.11). This was accomplished by using 20 bolts in a 5 x 5 pattern having two bolts missing in each of the second and fourth rows and one bolt missing in the middle row. Joint B6 increased the T/S ratio to 1.00/1.15 in a more compact 6 x 3 pattern (six lines and three transverse rows). This reduced the gage to 3" but the pitch remained at the original 3 1/2" value. The comparison riveted joint, BR2, was designed exactly like the bolted joint B2 so that a direct comparison of rivet strength to bolt strength might be made at a shear stress greater than presently allowed by specifications.

III. MATERIAL PROPERTIES

3.1 Plates

The plate used in the "B" joints was ASTM-A7 structural steel, cut from universal mill strips (of the same heat), 18" x 1" and approximately 72' long. A representative piece 18" x 4' was cut from the middle of each strip for coupon testing. A schematic diagram showing the location of the coupon material and the method of cutting individual coupons is shown in Fig 1. One half of the 72' strip was used to fabricate a "A" joint (using 1" bolts) and the other half used to fabricate a "B" joint. A comparison of actual to nominal dimensions of the plate material showed a variation of $+$ 0.5% to - 2.0% in the gross area.

Coupons were machined from the 1" plate to standard dimensions(13) having a cross sectional area of approximately 1.5 in^2 at the reduced section over an 8" gage length. The specimens were tested in the 120^k Tinius-Olsen machine using the automatic autographic strain recording device to obtain the stress-strain curve up to approximately the beginning of strain hardening. At this point the automatic recorder was removed from the specimen, and strain readings were taken with dividers to obtain the complete stress-strain curve through the plastic range. A cross head motion rate of 0.1 in/min was used (ASTM permits 0.5 in/min for an 8" gage length) while the automatic recorder was in operation, but after the recorder was removed the rate was increased to approximately 0.3 in/min in order to decrease test time in the inelastic range. Since several of the coupons exhibited a rising yield zone, the report of material properties includes two values of yield stress (1) the 0.2% strain offset yield stress, and (2) the static yield level. The typical stress-strain curve of Fig 2 indicates the method of obtaining these two values. A summary of material properties is shown in Table 3, "Results of Coupon Tests." The average coupnn yield stress is below the mill test value, but is above the minimum ASTM value of 33 ksi. Average coupon ultimate stress is approximately equal to the mill test value and is approximately at the average ASTM value. Variation in yield and ultimate stresses obtained in the laboratory compared to those obtained by mill tests has been explained by investigations(14) concerning the effect of strain rate on stress levels. Each coupon failure was typical of that for a ductile material.

In addition to the standard coupons, a full size, double plate "coupon" was tested. The specimen designated "P1", was fabricated from material of the same heat as the bolted joints. The specimen was tested in the 5000^k Baldwin machine, using wedge grips; and in one sense might be called a pilot test for the bolted joints since information regarding grip action at high loads, action of the seal weld used in the grip region, and load distribution across the plate was obtained. Elongation was measured over the 17" gage length of the reduced section (18" width was milled to 16.5", producing a "net" section greater than that of any of the bolted joints), and SR-4 strain gages were used to determine the strain distribution across the width of the plate. Figure 3 shows the stress-strain curve obtained from "P1" and Fig 4 shows the test set-up. The material properties compared favorably with those of the small coupons:

	"P1"	Coupons
0.2% offset yield stress	35.2 ksi	36.6 ksi
ultimate stress	65.1 ksi	65.5 ksi
percent elongation	26.5 %/17"	29.7 %/8"
percent reduction in area	31.0 %	56.8 %

Data from the SR-4 gages indicated uniform gripping action by the wedge grips.

3.2 Bolts

The bolts used in these tests were 7/8" ASTM-A325 high strength bolts (5 1/2" under head) with quenched and tempered washers and heavy semi-finished nuts. The bolts were furnished by the Lebanon Plant of Bethlehem Steel Company especially for this project, and were made to approach the lower limit of specification values; that is, they were minimum strength bolts. The combination of minimum strength bolt and average strength plate was chosen as a means of providing a more rigorous test of the bolts.

Before any phase of testing began, bolts were identified by stamping numbers on the head and shank ends, and were prepared for measurement by drilling small holes in the center of each end. Drilling was done with a special center drill which produced a beveled hole providing a protected bearing surface for the pointed tips of the measuring device. The initial or "zero" lengths of all bolts were determined by repeating measurements until three readings agreed within an over-all difference of 0.0002". Accurate measurements of the zero lengths were necessary since the change in bolt length (after torquing) would be related to internal bolt tension. Bolt measurements were made with an extensometer consisting of a "C" frame fitted with an adjustable length pointed tip at one end and a 0.0001" dial gage with a special pointed tip at the other end. A counterweight was fastened to the upper arm of the "C" so that the extensometer would balance in a vertical position when mounted on a bolt. This arrangement permitted measurements to be taken without touching the extensometer and thus eliminated errors due to deflection of the frame. A standard or zero bar, formed from drill rod and center-drilled in the same manner as the bolts, was used to check the extensometer setting before and after each sequence of measurements. Figure 6 shows the bolt extensometer and the zero bar.

It was decided to conduct laboratory "coupon" tests of the bolts and at the same time obtain a load-elongation calibration curve which might be used in determining the internal tensions of the bolts after they were torqued-up in the test joints. An average load-elongation curve, obtained by the method of direct tensioning described below, is shown as the upper curve in Fig. 7. To determine the internal tension of a bolt, one would enter the load-elongation curve with a measured change in length and read internal load directly.

Five bolts were chosen at random to be tested as representative of the lot. Loading fixtures, were designed to hold a single bolt in the 300^k Baldwin machine for direct tension loading. The bolts were fastened in the fixtures so that there was a 4" grip (same length of grip as in the bolted specimens) between the washers under the head and nut. Figure 5 shows the test set-up with the bolt extensometer in position for measuring.

The first stage of testing was the verification of the elastic proof load for each of the five bolts by the following procedure:

(1) The initial length of the bolt was recorded

(2) Load was applied in 4^k increments until the recommended elastic proof load was reached. (36.05^k for 7/8" bolts)

(3) Load was removed until the bolt was unloaded.

(4) The final length of the unloaded bolt was recorded to determine the amount of permanent set.

After unloading from the proof load value, none of the bolts showed a permanent set greater than the allowable tolerance of 0.0005" (L_f-$L_i \leq +$ 0.0005").

Following the verification of the elastic proof load, the bolts were reloaded to the proof load value and then loaded in 2^k increments to obtain the ultimate load and the complete load-elongation curve. In the inelastic range, load was held constant at each increment until the elongation of the bolt reached a stable value; sometimes this stabilization required 5 minutes. All bolts attained a load approximately equal to or greater than the recommended minimum ultimate load of 53.15^k based on a stress of 115 ksi on an area calculated from the mean root and pitch diameter of class 3 external threads. Results of the tests are shown in the following table:

Table 4

Direct Tension Tests of Bolts

Bolt No.	Lf-Li inches	Ultimate Load lbs
B45	+0.0005	53,200
B46	+0.0005	55,000
B47	+0.0002	56,000
B99	0.0000	53,000
B100	+0.0001	54,200
Specs:	$\leq$0.0005	53,150

The ultimate loads reported here were obtained without use of a 10° beveled washer under the bolt head as recommended by ASTM; however, this requirement is a test of ductility rather than strength, therefore there should be no reduction in the ultimate load unless the bolt failed at the bending section under the head.

Although the laboratory direct tension procedure of obtaining the load-elongation curve is a simple control for checking the internal bolt tension, it is known that a similar curve obtained by a torquing procedure will indicate lower values of internal bolt tension for a given elongation. In order to establish the difference of the tensions determined by each method, a calibration study was made to obtain load-elongation curves by a procedure of impact torquing of the nut. The bolts were mounted at a 4" grip in the Skidmore-Wilhelm device (a hydraulic load cell instrument), and the nut was torqued in angular increments by a standard impact wrench. Values of internal tension were recorded from the Skidmore-Wilhelm, and elongations were recorded from the bolt extensometer. Figure 7 presents a comparison of average test curves obtained by the two different procedures for calibration. A more complete report of the calibration study is being prepared at Fritz Laboratory.

Tests to determine the basic shear strength of single bolts were conducted by placing a bolt in a shear jig which produced double shear on the bolt by compressive loading in the 300^k Baldwin testing machine. Bolts were mounted in jigs with molycoted and non-molycoted faying surfaces, and were tensioned to various degrees of internal load. Bolts in the non-molycoted jigs failed at slightly higher load indicating that friction was carrying part of the load. Internal tension had no effect on the value of ultimate shear stress. The average ultimate shear for the 7/8" bolts of the "B" series was 80 ksi on the nominal area. A complete report of the shear study, including results of 7/8" and 1" bolts, is covered in a separate paper now being prepared at Lehigh University.

3.3 Rivets

The rivets used in BR2, the comparison riveted joint, were formed from 7/8" diameter ASTM-A141 structural rivet steel. Standard coupons[13] (0.505" diameter) were machined from three rivets chosen at random, and tested in the 120^k Tinius-Olsen machine using threaded grips. Table 5 lists rivet properties, and a typical test curve is shown in Fig 8. The automatic strain recorder, set at a 2" gage length, was used during the early stages of the test. An initial cross head motion rate of 0.01 in/min was used until the automatic recorder was removed at which point the rate was increased to 0.1 in/min (ASTM permits 0.2 in/min) and strain measurements were taken with dividers. Examinatinn of the test results indicates the only major difference from specifications to be the relatively high value of yield stress. The laboratory value of yield stress is also high compared to the mill reports; however, this difference is explained by the fact that mill reports refer to tests of the rivet stock, while the laboratory reports are based on tests of coupons cut from formed rivets.

Shear tests of single rivets, shop driven in jigs with mill scale faying surfaces (similar to the shear tests of the high strength bolts) indicated an average value of ultimate shear stress equal to 49.9 ksi.

IV. FABRICATION OF TEST JOINTS

4.1 Shop Procedure for Bolted Joints

All Shop work necessary in the fabrication of the test joints was carried out at the Bethlehem Steel Company fabrication shops in Bethlehem, Pennsylvania. The four pieces of plate used in the assembly of each joint were taken from the same rolling as shown in Fig 1. The four corner holes of each joint assembly were sub-drilled and reamed for alignment. Faying surfaces were cleaned of loose mill scale and burrs. All remaining holes were drilled through the solid four plies of material while the plates were held in alignment by steel pins in the corner holes. All holes were 15/16" diameter to allow 1/16" clearance for the 7/8" bolts. Since the test specimens were actually one-half of a butt joint, fill plates were required between the two outer plates in the gripping region (see sketch in Table II). The fill plates were welded in place with a continuous 1/4" bead weld to insure a uniformity of wedge grip action under test, and to prevent the falling of loose plate after joint failure. The gripping end of the inner plates was welded in a similar fashion. Joint assemblies were shipped with four temporary machine bolts in the corner holes.

4.2 Bolting-Up

The bolting-up operation was conducted at Fritz Laboratory by a Bethlehem Steel Company Erection Department field crew using their current field procedure for this type of work, namely, the "turn-of-the-nut" method(9). Using this method, the amount of nut rotation required to produce the desired internal tension depends on the diameter of the bolt and the grip length; for the bolts of the "B" joints the necessary rotation was 1/2 turn from the snug position.

When tightening B3, the standard tightening procedure was slightly modified so that information regarding the relaxation of fitting-up bolts might be obtained. The laboratory procedure for bolting B3 was as follows. The pneumatic impact wrench which was to be used for tightening the bolts was checked on the Skidmore-Wilhelm calibration device to determine if the wrench would produce sufficient internal tension (recommended value 37,000lbs). With the joint in the edge position, holes were faired-up with tapered pins, and the shipping bolts were removed. Bolts were placed in the remaining holes and a pattern of fitting-up bolts (see Fig 7) was chosen similar to the procedure used for riveting. The impact wrench was used to spin the nut of each fitting-up bolt to the snug position and then tighten 1/2 turn while the head of the bolt was held by a spud wrench. "Snug" was indicated by the wrench when it began to impact. By use of painted marks at 90° increments on the chuck of the impact wrench it was possible to keep an accurate record of the amount of turn given to each nut. After all fitting-up bolts were tightened, the joint was lowered to a flat position so that the change in length of the fitting-up bolts could be measured with the bolt extensometer. The joint was returned to the edge position and the remaining bolts were snugged-up and then tightened one-half turn. The pins used for fairing-up the holes were then replaced by bolts which were tightened as above. The joint was returned to the flat position and the fitting-up bolts were again measured to determine if they had relaxed due to tightening the neighboring bolts. The joint was again raised to the edge position and a check or "touching-up" of the fitting-up bolts was made by attempting to turn each nut with the impact wrench. The operator of the wrench decided by the "feel" of the wrench impacting whether further tightening was necessary. Some bolts required as much as an additional 1/4 turn while others did not require any additional turning.

Measurements of the fitting-up bolts with the bolt extensometer showed a relatively small amount of relaxation when the neighboring bolts were tightened. The greatest relaxation noted was 0.0014" (for bolt #87 in B3) and this corresponded to a loss of approximately 4400 lbs internal tension based on an average calibration curve. During the process of "touching-up" the fitting-up bolts, bolt #87 was given another 1/4 turn, and this additional tightening more than restored the tension lost due to relaxation. The average internal bolt tensions for all bolts, as determined from the calibration curves (Fig 7) was above the recommended minimum value.

The bolting procedure for the other joints followed the standard field procedure, differing from that of B3 in that no intermdeiate measurements of fitting-up bolts were recorded. After the selected pattern of fitting-up bolts was tightened, they were "touched-up" at the same time the neighboring bolts were tightened across the joint. This procedure follows the actual field practice, and is believed to work any looseness or slack out of the joint.

Examination of the elongation data in Table 6 shows that the average bolt elongation of the first group of joints (B1, B2, B3) was greater than that of the second group of joints (B4, B5, B6). This is explained by the fact that the two different groups of joints were tightened at two different times by two different bolting crews. Values of individual bolt elongations are plotted along the horizontal scale of the calibration curves in Fig 7, where it may be seen that although there is considerable scatter for the values of elongations, there is little difference in the value of internal tension for each bolt since the elongations occur at the part of the calibration curves where load is relatively constant.

4.3 Shop Procedure for Riveted Joint

The fabrication of the comparison riveted joint, BR2, was carried out at the same time as the fabrication of joints B4, B5, and B6, and in a similar manner. Holes were drilled through the 4 plies of material after the corner holes had been sub-drilled and reamed, and the plates fastened in position with four pins in the corner holes. The joint was then riveted according to ordinary shop riveting practice while observed by Lehigh personnel.

V. INSTRUMENTATION

5.1 Introduction

Instrumentation of the test specimens included use of the following equipment:

(1) electric strain gages (SR-4) for measuring strains in the main and lap plates;

(2) slide bar extensometer for measuring elongations between each transverse row of bolts;

(3) electric clip gages for measuring elongations between each transverse row of bolts at loads near ultimate;

(4) dial gages (0.001") for measuring slip between the main and lap plates;

(5) dial gages (0.001") for measuring total elongation of the joint within the bolt pattern.

The instrumentation set-up was not identical for all tests, but was gradually developed as each completed test yielded additional information Figure 9 shows the instrumentation layout for each specimen.

5.2 Electric Strain Gages

Strains were measured in the main and lap plates with SR-4 Type A1 gages. Gages located within the bolt pattern were placed at the center of the small rectangle formed by four adjacent bolts. Results of the first three tests indicated that one gage between each transverse row of bolts provided reliable information, and it was therefore possible to eliminate several gages from the bolt pattern. Gages located on the gross section of the lap plates were placed 3" from the end of the main plate, and gages on the gross section of the main plates were place 3" from the end of the lap plates. The consistent data of these gages permitted using two at each location rather than the original four used in B1. In Joint B2, two extra gages were mounted on the West lap plate outside the bolt pattern and in line with the gages between the first two transverse rows of bolts. It was suspected that strains near the edge of the plates might be different from those measured within the bolt group, however this was not the case, and this location was not used again. Gages were mounted on the edges of both the main and lap plates of B2 and B3, but in later tests the lap plate gages were omitted as superfluous. The procedure of locating gages on the edge of the main plates was continued since this was the only accessible portion of the main material within the bolt pattern.

5.3 Slide Bar Extensometer

The slide bar extensometer was an instrument used to measure the plate elongations between transverse rows of bolts. This instrument was used to measure the large in-elastic deformations over the pitch distance of the bolted joints, a measurement which was not possible with the SR-4 gages. It consisted of two main parts; a sliding bar, and a fixed frame which provided a machined track for the sliding bar. Gage points were fastened to each piece at approximately the 3 1/2" pitch distance of each joint. A 0.0001" dial gage was mounted on the fixed frame so that as the gage points moved apart the dial would record the amount of separation. Small holes, similar to those used in the bolt measurement procedure, were drilled in the lap plates at points midway between two bolts on each transverse bolt row. Holes were also drilled in the edges of each main plate on the vertical centerline and in line with each bolt row. The holes provided seats for the gage points of the extensometer. Taking elongation measurements consisted of merely placing the extensometer in the proper holes and recording the dial reading. Figure 10 shows the slide bar extensometer in use. The extensometer was used for measuring pitch elongations in joints B4, B5, B6, and BR2.

5.4 Electric Clip Gages

In an attempt to develop an inexpensive, destructable gage for safely measuring plate elongations over the pitch distance at loads near rupture, the electric clip gage was devised. The gage consisted of a thin strip of aliminum (3/8" x 3/64" x 8") bent in an arch with the ends turned up approximately normal to the curvature and drilled for mounting on the face of the test joint plates at points between two transverse rows of bolts. Two SR-4 strain gages were bonded to the aluminum strip at the center of the arc on the top and bottom. As the ends of the gage moved apart, curvature changed, and the strain gages responded. Each clip gage was calibrated by forcing a known separatinn of the gage ends as measured by a 0.0001" dial gage, and recording the coresponding change in strain measured by the SR-4 gages. This procedure produced a calibration curve for each clip gage. Clip gages were used on specimens B4, B5, and B6.

5.5 Slip Gages

Dial gages (0.001") were mounted with a system of small welded brackets so that the relative movement of the inner and outer plates of the test joint could be measured. The brackets were spot welded to to the plate material at each transverse bolt row. The slip gage arrangement is shown in Fig 12, an oblique view of Joint B2. Joints B1, B2, and B3 were fitted with slip gages on both the North and South edges, but this practice was discontinued for the tests of B4, B5, and B6. In testing BR2, the riveted joint having the same pattern as B2, slip gages were mounted on the North edge in order to make a comparison with the results of the B2 test.

5.6 Joint Elongation Gages

Measurement of total elongation of the test joint within the fastener pattern was recorded by use of one 0.001" dial gage on each face of the joint. The dial was fastened to a stud welded on the main material at a point on the vertical centerline and 2 3/4" away from the center of the end row of fasteners (approxiamtely 1" from the edge of the lap plate). The dial plunger rested on a pedestal on the end of a long rod which was fastened to a stud welded to the lap plate at a position similar to the stud on the main plate. This arrangement may be seen in Fig 12. All test joints were fitted with joint elongation gages as described above.

VI. TEST PROCEDURE

All of the test joints were tested to failure in the 5000^k Baldwin machine, using flat wedge grips to apply the load. Figure 11 shows one of the bolted joints mounted in the test machine before testing. No special precautions were taken with alignment of the specimens. The general procedure was as follows:

(1) The specimen was mounted in the test machine, fitted with the desired instrumentation, and partially enclosed with a protective screen at both faces.

(2) "No-Load" readings of all gages were recorded.

(3) The specimen was gripped with a load of 100^k, and "zero" readings of all gages were recorded.

(4) Load was applied in 100^k increments until major slip was experienced, gages being read at each loading.

(5) At major slip, the testing machine would drop load due to the sudden displacement and stablize at the lower value; gages were read after the stabilization.

(6) Load was applied in selected increments until the slip load was again reached, gages being read at each increment.

(7) Load was applied again in 100^k increments, allowing time for stabilization in the inelastic range; this required about 10 minutes.

(8) Dial gages were removed and the working scaffold dismantled when the predetermined danger point was reached.

(9) Load was applied to failure, reading SR-4 strain gages where possible.

VII. TEST RESULTS

7.1 Bolt Relaxation

Prior to each tension test of the bolted joints, all bolts within that joint were measured by the bolt extensometer to determine if any relaxation had occurred since the time of bolting. Any change in length from that recorded after the joint was bolted-up would indicate a loss of internal tension, and therefore less total clamping force. No relaxation of the 7/8" bolts of the "B" joints was recorded after more than three months from the initial bolting-up date. Similar measurements of 1" bolts used in another phase of the over-all testing program showed no relaxation over a ten month period of time.

7.2 Description of Joint Behavior Under Test

A summary of the results of the "B" series of tests is given in Table 6. During the early stages of each test, the joints experienced what has been called minor slip, characterized by a small decrease of testing machine load and a small increase in displacement as indicated by the slip and total elongation gages. Major slip occurred at some higher load and was easily distinguished by a characteristic resounding "bang" accompanied by a sudden and considerable decrease of load by the testing machine and a large increase in displacement of the inner and outer plates, equivalent to approximately the hole clearance. As additional load increments were applied after major slip, periodic noises, sounding like a scraping or grating of the plate surfaces accompanied by decreases of testing machine load of from 5^k to 10^k, were noted. This was believed to be caused by further slipping into complete bearing; since, due to the artificial condition of dropping load created by the testing machine (in an actual structure the load would remain constant) the specimens were not initially forced to slip into full bearing at the major slip load, but experienced instead a partial slip.

The specimens failed by tearing the plate material, shearing all fasteners, or shearing a single fastener accompanied by a substantial drop of load. In all tests, except that of B3, there was no distinction between ultimate and rupture loads. A discussion of each test is given below.

Joint B1 (T/S = 1.00/0.74) exhibited a minor slip at 1200^k and then continued carrying load until major slip occurred at 1238^k or a nominal bolt shear of 34.3 ksi. Figure 13a gives the load-elongation curve for B1. Failure by tearing the two main plates through the net section at the top row of bolts occurred at a load of 1956^k. Figure 14 of the ruptured joint shows necking of the plates and lateral bending of the corner bolts. Ultimate stress on the net section was 73.5 ksi as compared to 68.5 ksi coupon ultimate, for a net efficiency of 107%.

A minor slip at 200^k was noted for Joint B2 (T/S = 1.00/0.89); however, the specimen continued to take load until reaching 1047^k (nominal bolt shear of 34.9 ksi) when major slip occurred. (See Fig 13b) The joint failed by tearing one of the lap plates through the net section at the bottom row of bolts. The ultimate stress on the net section of 73.2 ksi was greater than the coupon ultimate of

66.3 ksi by approximately 10%. The ruptured joint is shown in Fig 15.

The load-elongation curve for Joint B3 (T/S = 1.00/1.11) is shown in Fig 13c. For this specimen, minor slip was indicated at 600^k and again at 900^k. Major slip was noted at a nominal bolt shear of 38.0 ksi when load reached 911^k. Failure consisted of three stages: (1) at 1750^k, bolt #84 (top, north corner) sheared the nut end off, the shank remaining in the hole, and load dropped to 1650^k; (2) while load was being held constant at 1650^k, bolt #99 (bottom, north corner) sheared in the same manner and load dropped to 1630^k; (3) load was applied and the remaining 18 bolts sheared in unison at 1680^k. The final rupture load was 70^k lower than the load which produced the first corner bolt shear failure. A considerable bend in the West lap plate (head end of bolt) can be noticed in Fig 16 of the ruptured joint. It is believed that this bending was caused when the remaining 18 bolts sheared the nut ends, thus shifting the specimen to a single lap joint which attempted to realign in the instant before complete failure. Figure 17 gives a close-up of the bolt failures showing their relative position in the joint. Figure 17 also shows that the shearing plane of the bolt failures is not through the reduced area at the threaded end (which might be suspected since that end of the bolt sheared first) but is at the section of full shank area. Although the specimen failed by bolt shear, the net section had developed a stress of 65.8 ksi which was identical to the corresponding coupon strength.

A load-elongation curve for Joint B4 (T/S = 1.00/0.96) is given in Fig 13d. Minor slip was recorded at 720^k, at 778^k, and at 800^k. Major slip was reached at 850^k or a nominal bolt shear of 30.7 ksi. The specimen exhibited frequent noises and accompanying minor slips at higher load levels as the bolts apparently slipped into complete bearing. The joint failed at a load of 1786^k by tearing of one lap plate through the net section at the bottom row of bolts (similar to the failure of B2). Figure 18 is a general view of the failure, and Fig 19 gives a close-up of the torn lap plate. Necking of the main plate and the relative displacement of the main and lap plates may be seen in Fig 20. An edge view in Fig 21 shows how the joint had started to bend the intact lap plate in an attempt to realign what had become a single lap joint. This is the process which probably explains the bending of the lap plate of B3. At failure, the specimen developed a stress of 67.1 ksi on the net section, compared to a coupon strength of 63.5 ksi, for a net efficiency of 105%.

Joint B5 (T/S = 1.00/1.11) exhibited several minor slips: at 319^k, at 514^k, and at 518^k. The load-elongation curve of Fig 13e shows major slip at a load of 609^k or a nominal bolt shear of 25.4 ksi. As load was being increased in an attempt to reach the major slip level again, the joint again slipped at a load of 550^k. From 600^k up to a load of 1000^k the joint periodically indicated a gradual slipping action. At a load of 1680^k failure occurred by shearing a single bolt (bottom, south corner) and dropping load to 1500^k. The test was stopped. As in the B3 test, it was the nut end which sheared off, leaving the bolt shank in the hole. Figure 22 shows a general view of the B5 failure, and Fig 23 shows the sheared surface of the bolt shank and the bearing deformation of the hole. At the time the bolt sheared, tension on the net section was 63.2 ksi compared to 64.3 ksi coupon strength.

Joint B6 (T/S = 1.00/1.15) indicated minor slip at 320^k and then continuously at approximately 50^k intervals until major slip occurred. The major slip load was recorded at 673^k (nominal bolt shear = 31.2 ksi). Minor slipping action, accompanied by intermittent noises was indicated until load reached 1100^k. Testing was stopped when the head end of a single bolt (top, north corner) sheared off and load dropped from 1550^k to 1485^k. Figure 24 gives a general view of the specimen and Fig 25 shows the sheared surface of the bolt shank and the hole deformation. At failure, tension on the net section was 62.6 ksi.

A curve of load-elongation characteristics for BR2, the comparison riveted joint, is given in Fig 13f. Joint BR2 (T/S = 1.00/0.89) showed minor slip characteristics similar to those of the bolted joints, slipping at 318^k, 524^k, and 622^k. A major slip was recorded at a nominal rivet shear of 21.8 ksi, when load reached 654^k. This was followed by periodic slips until ultimate load of 1300^k when failure occurred by simultaneous double shearing of all rivets. The net section had developed 48.9 ksi compared to coupon strength of 64.6 ksi. At rupture the shank and the manufactured head fell from the specimen in two pieces, but the driven head remained lodged in the one lap plate. Large deformations of the rivet holes were observed, particularly at corner holes. Bending of one lap plate occurred similar to that observed in the failure of B3.

7.3 Plate Strains - SR-4 Gages

Strain distribution, as measured on the East and West faces of the specimens by the SR-4 gages indicated very good alignment of the joint in the testing machine, and good gripping action. Figures 26, 27, and 28 show the plate strains of Joints B1. The data of B1 was chosen here since the pattern of SR-4 gages on the plate faces was most complete for that joint. (See Fig 9) Figure 26 illustrates the uniform strains of the main and lap plates as measured on the gross sections at various load levels. At the 1200^k level, the gross section is at coupon yield stress; therefore, gage readings become erratic. Figure 27 indicates the strain distribution within the bolt pattern between the third and fourth rows of bolts (on the horizontal centerline of the bolt pattern for B1). It can be seen here that the strains in each lap plate are, for all practical purposes, equivalent at each load level.

Figure 28 shows the relative magnitudes of the lap plate strains between each row of bolts for the East face of B1. (It has been shown in Fig 26 and 27 that the strains of either the East or the West plate may be considered representative of the lap plate strains.) Each point on the curve represents the average of the strains measured by the four SR-4 gages in that row. At loads below yield on net section, each line is in what could be called its "correct" relative position; that is, the gages of row 2-3 (gages between the second and third row of bolts) would be expected to show more strain than the gages of row 1-2 since the lap plates receive an additional portion of the load at every transverse bolt row. Since in the elastic range a curve of load vs strain will be a straight line, some idea of how the load is carried within the joint may be obtained by noting when each curve of Fig 28 begins to deviate from the original slope; that is, when the load at each section caused inelastic behavior. The curve plotted from the data of the gages in row 5-6 follows very closely to that of the gross section and eventually crosses that line, thus indicating a greater unit strain at that section than at the gross section where full load is being carried. This action is explained by the fact that the gages of row 5-6 are within the bolt pattern and are influenced by net section to some degree. Evidence supporting this idea is that the load at which the slope of the 5-6 curve changes and becomes flatter than the slope of the gross section curve is approximately midway between the calculated loads producing yield on net section and gross section.

Examination of the curve representing the data of the gages in row 1-2 (Fig 28) reveals the interesting fact that at loads greater than 1450^k the gages are recording a decrease in strain, or what could be called the presence of a compressive stress. A possible explanation may be that at these high loads, the first row of bolts is bending so that each bolt produces a resultant couple, or moment, acting on the plate at the holes nearest the free ends of the lap plates, thus causing a compressive bending stress at the outside surface. These compressive stresses are greater than the tensile stress caused by the longitudinal loading of the joint at this section which carries the least load, hence the decrease in measured strain.

Strains of the two inner or main plates as measured by the SR-4 gages indicated each plate was carrying an equal share of the load. Figure 26, comparing the East and West faces shows this very well. Figure 29 indicates the relative magnitudes of the main plate strains within the bolt pattern as obtained from the average of opposite gages on the North and South edges of Joint B3. The data of B3 is presented here since this was the first joint to be provided with a complete set of gages on the edges of the main plate. Here again, as in the curves plotted for strains in the lap plates, the curves remain in their "correct" relative position until the load reaches a level in the vicinity of that necessary for yielding on the net section. At that load level, the curve plotted from the data of edge gages between the first two rows of bolts (at the section where the main plates carry the greatest load within the bolt pattern) changes slope considerably, and indicates greater strains than measured on the gross section.

Figure 30 presents the strain data for each row of gages on the West lap plate of B3. By comparing Fig 29 and 30 a complete strain picture for a single joint may be examined.

7.4 Plate Strains - Slide Bar Extensometer

Strain measurements obtained from the data of the slide bar extensometer verified the information obtained from the electric strain gages in regard to even distribution of load across any transverse section of the joint. This was a valuable check since in the later tests the SR-4 gages were arranged in a single vertical line on each face of the bolt pattern.

An attempt was made to correlate measurements of the slide bar extensometer and the SR-4 gages at locations where the slide bar gage points straddled the electric strain gages. In order to make a direct comparision it was necessary to convert the elongations measured with the extensometer to unit strains, by dividing by the the extensometer gage length of 3.5". A reasonable agreement of the two methods of obtaining unit strains was found for values in the elastic range. No data obtained from the slide bar extensometer is presented here, since this information is not directly related to this paper, but will be used in a study of the failure mechanics of the bolted joints in a later paper.

7.5 Plate Strains - Electric Clip Gages

Results of measurements made by the electric clip gages are inconclusive because of erratic behavior. No correlation between this data and that obtained by the SR-4 gages or slide bar extensometer has been found; therefore, this procedure will not be pursued further.

7.6 Joint Slip

It has already been mentioned that each of the joints possessed certain slip characteristics such as the frequency of minor slips, the magnitude of the major slip load, and occurrence of a partial slip. Looking at the patterns of the first three specimens, one might easily explain why the major slip loads were in the ratio B1 > B2 > B3. Since all bolts were torqued to approximately the same internal tension (as shown by the bolt calibration curves, Fig 7) the amount of clamping force in each joint should vary according to the number of bolts; therefore, if the frictional force or slip load is calculated as a function of clamping force, the slip loads should vary as B1 > B2 > B3, because B2 used 5 fewer bolts than B1 and B3 used 5 fewer bolts than B2. This was the case, since the three slip loads were: B1= 1238^k, B2 = 1047^k, B3 = 911^k. Considering Joint B4 which had 23 bolts (three more than B3) it would be expected that the slip load would be slightly higher than that of B3, however this was not the case. The same contradiction is seen in the data of B5 which used the identical number of bolts as in B3, but slipped at a much lower load (609^k vs 911^k). The explanation for these differences seems to be shown by a closer examination of the bolt patterns (see Table 2). Joints B4 and B5 utilized what might be called "open" patterns, and for that reason probably did not obtain a uniform distribution of clamping force. Joint B6 presented the most compact pattern of the six bolted joints, and actually developed a greater slip load than B5 which used two more bolts, however considerable minor slip was reported for B6. The riveted joint, BR2, slipped at a load which was approximately 60% of that developed by the comparable bolted joint, B2. This merely points to the already known fact that the clamping force of a rivet is variable and may be quite low. The fact that a major slip was indicated shows that the rivets did not completely fill the holes.

The nominal coefficient of friction was calculated for each of the bolted joints by use of the equation $\mu = F/N$, where "μ" is the coefficient of friction, "F" is one half of the slip load (because the load is divided between two lap plates), and "N" is the average total clamping force for the bolt group. A tabulation of friction coefficients is included in Table 6. In determining the clamping force which is to be used in calculating the friction coefficient, either of the two bolt calibration curves of Fig 7 might be used, each giving a different value of clamping force and therefore providing two different values for the coefficient of friction. Clamping force obtained from the "torqued" calibration curve would be lower than that obtained from the "direct tension" calibration curve; therefore the value of "μ" would be higher when calculated for the same slip load. The values of "μ" reported in Table 6 are based on the direct tension bolt calibration curve, and are in the vicinity of 0.40.

Slip as measured by the dial gage arrangement discussed under "Instrumentation" is actually a relative displacement between the main and lap plates; the displacement being due to the combined effect of sliding of the plate surfaces and of elastic and inelastic strains between each bolt row. The measurement of this "slip" is of interest because it should be of assistance in predicting joint failure based on fastener deformation.

Slip gage data was obtained from joints B1, B2, B3, and BR2. Inspection of the data from the first three joints for which gages were mounted on both North and South edges showed excellent agreement between opposite gages at corresponding levels. This symmetry about the vertical centerline indicates symmetrical loading of the specimen. As load increments were applied to a joint, the gages responded in an order depending on their position in relation to the center of the joint; that is, the top and bottom gages were always the first to respond, followed by the second gage from the top and the next to last gage, etc. This symmetry about a horizontal centerline indicates a symmetrical partition of load. The slip data for joints B2 and BR2 is shown as load vs slip curves in Fig 31 and 32. Due to the symmetrical nature of the data as described above, curves are plotted for only the upper half of the joint. In Fig 31, each point represents the average of two opposite gages since gages were mounted on both edges of B2.

The plate displacements measured by the slip gages may be classified under two main headings, minor slip and major slip. Minor slip is a very small displacement and is local in nature. Major slip is a large displacement which occurs simultaneously throughout the bolt pattern, placing all of the bolts in bearing. The displacement between the main and lap plates measured at major slip of the bolted joints was in the vicinity of 0.08" which is approximately the hole clearance. For the riveted joint, the major slip plate displacement was approximately 0.02".

7.7 Joint Elongatinn

Curves plotted from the load-elongation data of the test joints (Fig 13) revealed that the bolted joint is actually stiffer (produces less elongation per load increment) than the gross plate material from which it is fabricated, while the riveted joint is only slightly stiffer than the net section. The curves shown in Fig 13 compare the joint elongation data in the elastic range to the elastic lines obtained from the well known deflection formula, e = PL/AE, where "e" is total elongation, "P" is total load, "L" is the gage length, "E" is Young's Modulus (30,000 ksi), and "A" is the area of the section, using first net area and then gross area to obtain the two straight lines. In all cases the experimental curve obtained from the bolted joint data presented a greater slope than the two theoretical elastic lines, but the curve plotted from the data of the riveted joint followed closely to the elastic line based on net area. The data of B6 is omitted from this discussion since the dial gages were not functioning properly for that joint.

In an effort to develop a technique for predicting elongation within a bolted joint of this type it was decided to determine some "effective" area which when used in the deflection formula would result in a correct value for total joint elongation within the bolt pattern under elastic loading conditions. Area was chosen as the "effective" variable since in a given joint, "P" and "L" will be given, and an effective value of "E" might lead to confusion in design. The deflection, or elongation formula was solved in terms of area and written in the form $A_{eff} = \triangle P / \triangle e \cdot / L / E$, where $\triangle P / \triangle E$ is the slope of the experimental curve. In order to obtain the true slope defined by the experimental data calculations were made according to the "Method of Least Squares". The calculated value of $\triangle P / \triangle e$ was then used to determine "A_{eff}". A tabulation of the results and a comparison to the gross area of each joint, "A_g" is given below.

Joint	A_g	A_{eff}	A_{eff}/A_g
B1	36.1	45.0	1.25
B2	36.2	42.5	1.17
B3	35.5	38.4	1.08
B4	35.6	38.5	1.08
B5	35.3	35.8	1.01
BR2	35.6	27.1	0.76

In no case was the effective area of the bolted specimen less than the gross area of the section; however, the effective area of the riveted joint was considerably less than gross area, and was only slightly greater than the actual net area of 26.2 in^2. Since the only major difference between the bolted joints and the riveted joint was the magnitude of the clamping force, it seems reasonable to conclude that clamping force is the probable "stiffening" agent. It might also be concluded from this discussion that in calculating elongation of a bolted joint loaded in axial tension, reasonably accurate values would be obtained by using an effective area equal to the gross area of the main material, providing major slip does not occur. Elongations calculated in this manner should be greater than those which would actually occur.

A direct comparison to the bolted joint, B2, and the riveted joint, BR2, is shown in Fig 33 and 34. Figure 34 presents the early stages of the load-elongation curve plotted to a magnified elongation scale. The "dashed" portion of the curve represents the artificial drop of load by the testing machine at major slip, and the "solid" line indicates the action of a real structure.

VIII. SUMMARY AND CONCLUSIONS

Based on the results of the static tension tests of the previously described compact butt type joints, fastened with 7/8" A325 bolts, the following Summary and Conclusions are suggested.

8.1 Tension - Shear Ratio

An immediate conclusion based on the test data is that the present specifications for T/S = 1.00/0.75 is definitely conservative for compact bolted joints under static loading. Plate failures in the bolted joints at tension-shear ratios of 1.00/0.89 and 1.00/0.96 suggest a change to equal values of allowable stresses for tension and shear in joints of this type. However, examination of the data from joints which failed by shear of bolts at values of T/S up to 1.00/1.15 reveals that in all cases the net section had developed stresses greater than the minimum allowable ultimate. Since minimum strength bolts were used in these tests it seems that a tension-shear ratio of 1.00/1.10 would provide safe, balanced design. This ratio would correspond to an allowable shear stress of 22 ksi on the nominal area of the bolts when 20 ksi is allowed on the net section. It is interesting to note that none of the bolted specimens experienced major slip at a nominal bolt shear less than 25.4 ksi, this being the value developed by the open pattern of Joint B5. (Table 6)

8.2 Joint Slip

The slip into bearing of a bolted joint apparently is not only dependent on the clamping force of the fasteners, but is also dependent on the fastener pattern. Solid patterns (that is, no omitted bolts) in which the bolts were arranged in a compact group produced the best slip resistance. The compact arrangement is also desirable from the point of view of least weight of material. The total plate displacement, or major slip, for a bolted joint places all bolts in bearing simultaneously, and is approximately equal to the hole clearance. (Fig 34).

8.3 Joint Elongation

A bolted joint stressed by working loads produces less total elongation than would be predicted for the solid plate material from which the joint was fabricated. (Fig 13) The stiffening agent seems to be the high clamping force of the bolts. Estimates of total elongation for compact pattern joints (before slip occurs) may be obtained by using an effective stressed area equal to the gross section of the main material.

8.4 Bolt Tensions

Internal bolt tensions obtained by the "turn-of-the-nut" method are above the specification minimum, and are of consistent magnitude regardless of slight variations in the change of bolt length produced by tightening. (Fig 7) In the several months time that elapsed between bolting and testing of the joints, no single bolt measurement indicated any relaxation. Loss of tension in fitting-up bolts caused by tightening neighboring bolts in the pattern was more than compensated by the "touching-up" procedure.

8.5 Tension Failures - Net Efficiency

Stresses developed by the net section of the bolted joints which failed by tearing of the plate material were always greater than the ultimate strength indicated by the related coupon tests; that is, net efficiency was greater than 100%. (Table 6) This phenomena has been observed by other investigators(6) who have reported net efficiencies greater than 100% for test joints having a value of "g/d" less than 8. The value of "g/d" for the "B" joints was approximately 4, therefore a net efficiency above 100% might be expected.

8.6 Shear Failures - Fastener Efficiency

In cases for which bolt shear was the criterion for failure, a corner bolt was always the first to fail. Failure of corner fasteners has been noted in other tests of riveted and bolted joints,(11, 12) and is attributed to the additional bolt load in the lateral direction due to necking of the highly stressed sections. Evidence of this lateral force is found in examination of the hole deformations of specimens which failed by shear. Corner holes in the plate material have been distorted to elliptical shapes having the major axis inclined at a considerable angle to the longitudinal axis of the test joint; thus indicating a resultant shear force composed of longitudinal and lateral components. Average nominal bolt shear stress at failure was approximately 90% of the ultimate shear stress reported in tests of single bolts in double shear (80 ksi).

The failure of the riveted joint, BR2, was a simultaneous shear of all fasteners, thus indicating an equal distribution of load among the rivets at ultimate load. Average nominal shear for the rivets of BR2 was approximately 87% of the ultimate shear stress reported in tests of single rivets in double shear (49.9 ksi).

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X. APPENDIX

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10.2 Definition of Terms

An alphabetical list of various terms and symbols as used in this report is given below with a brief definition or explanation.

(1) Average Total Clamping Force: The force obtained by entering the load-elongation bolt calibration curve (Fig 6) with the average elongation of a given bolt group and multiplying the corresponding internal bolt load by the number of bolts in that group.

(2) Coefficient of Friction: $\mu = F/N$, where "F" is one-half of the major slip load, and "N" is the average total clamping force. Two values of "μ" exist, depending on which curve of Fig 6 is used to obtain the clamping force.

(3) Direct Tension Load-Elongation Curve: Relation of internal bolt tension to bolt elongation, determined by pulling a single bolt in static tension at a prescribed grip.

(4) Elastic Proof Load (EPL): The limiting load beyond which permanent deformation of the bolt occurs.

(5) Fitting-Up Bolt: A bolt used to draw the plies of plate material sufficiently tight before the remaining bolts of the pattern are tightened.

(6) g/d: Expresses the ratio of gage (transverse spacing) to the actual diameter of the hole in the plate. Used in discussions of joint efficiencies.

(7) Gross Efficiency: Ratio of ultimate stress of the gross section of the test joint to the ultimate stress of the corresponding coupon.

(8) $(L_f - L_i)$: Difference between final and initial bolt lengths. Used in checking the EPL.

(9) Major Slip: Sudden, large relative displacement of inner and outer plates of the test joint. (0.08" for bolted joint and 0.02" for the riveted joint)

(10) Minimum Required Tension: 90% of the EPL

(11) Minor Slip: Very small relative displacement of the inner and outer plates of the test joint.

(12) Net Efficiency: Ratio of ultimate stress developed by net section of the test joint to the ultimate stress of the corresponding coupon.

(13) Recommended Bolt Tension: 15% in excess of the minimum required tension.

(14) Skidmore-Wilhelm Device: An instrument made up of a hydraulic load cell and a bourdon gage which reads directly the amount of internal bolt tension induced by torquing. Used in the field to calibrate impact wrenches.

(15) Snug: The expression used to describe the tightness of a bolt before beginning the half turn of the nut. "Snug" is indicated by the impact wrench when impacting begins.

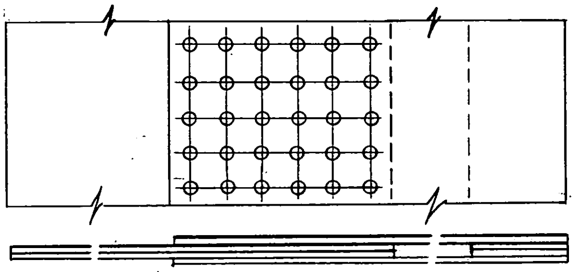
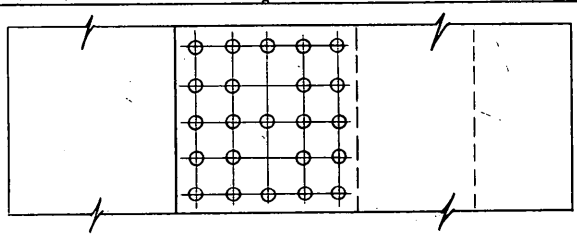
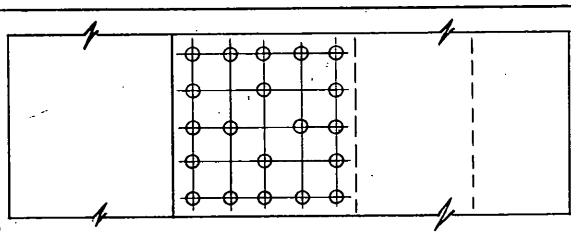
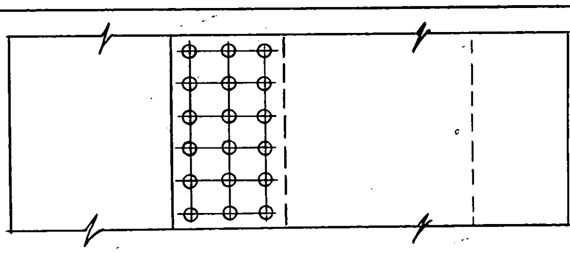
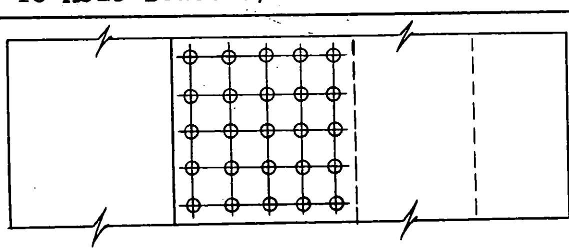
(16) T/S: Ratio of net tensile stress to shear stress on the gross or nominal area of the fasteners in a structural joint.

(17) Torqued Load-Elongation Curve: Relation of internal bolt tension to bolt elongation, determined by impact torquing the nut of the bolt which is held at a prescribed grip.

TABLE 1

NO.	VARIABLE	REMARKS
1	Type of load	Static load only
2	Position of load	Axial load only
3	Temperature	Room temperature
4	Type of material	ASTM-A7 Steel
5	Type of joint	One-half of butt joint
6	Number of plies	All four plies
7	Length of joint	Varies from 2 "pitches" to 5 "pitches"
8	Pattern	Varied by omitting bolts; no staggering
9	Pitch	Constant at 3 1/2"
10	Gage	Constant at 3 5/8" except B6-3"
11	T/S	Varied by omitting bolts
12	Faying surface	All mill scale; degreased
13	Size of hole	All 15/16"
14	Type of hole	All drilled
15	Hole alignment	Drilled through four plies
16	Fastener type	A325 bolts and A141 rivets
17	Fastener size	All 7/8"
18	Tensioning method	Impact wrench, observe turn of nut
19	Bolt tension	Governed by half turn of nut
20	Grip	All 4"

TABLE 2

MARK	PATTERN	T. S. RATIO	GAGE IN.	PITCH IN.
B1	 4-Pls. 18" x 1" x 7'1" 2-Pls. 18" x 1" x 2'4"(Fill at grip) 30 A325 Bolts 7/8" diameter	1.00/0.74	3 5/8" g/d*= 3.87	3 1/2" p/d = 4.0
B2	Same as B1 except 5 rows-25 bolts	1.00/0.89	"	"
B3	Same as B1 except 4 rows-20 bolts	1.00/1.11	"	"
B4	 23-A325 Bolts 7/8" diameter	1.00/0.97	"	"
B5	 20-A325 Bolts 7/8" diameter	1.00/1.11	"	"
B6	 18-A325 Bolts 7/8" diameter	1.00/1.14	3" g/d*= 3.20	"
BR2	 25-A141 Rivets 7/8" diameter	1.00/0.89	3 5/8" g/d*= 3.87	"

* "d" is diameter of drilled hole

TABLE 3

RESULTS OF COUPON TESTS

Coupon Number	Static Yield Level psi	Avg. Static Yield Level psi	Yield Stress .2% Off-set psi	Avg. Yield Stress .2% Offset psi	Ult. Tensile Stress psi	Avg. Ult. Tensile Stress psi	Perc. Elong. in 8" %	Avg. Perc. Elong. %	Perc. Reduct. In Area %	Avg. Perc. Reduct. In Area %
A1B1-1 -2 -3	32,800 34,900 36,700	34,800	41,500 36,000 38,000	38,500	74,000 66,400 65,200	68,500	30.4 29.4 31.0	30.3	54.4 42.6 57.5	51.5
A2B2-1 (G1)-2 -3	32,000 36,600 37,000	35,200	39,900 38,500 38,400	38,900	65,400 68,800 64,700	66,300	24.7 23.1 30.0	25.9	58.6 34.3 56.3	49.7
A3B3-1 -2 -3	32,800 34,400 35,300	34,200	33,400 34,500 35,100	34,300	64,700 67,400 65,400	65,800	31.7 27.2 27.0	28.6	58.8 40.3 46.7	48.6
A4B4-1 -2 -3	33,600 29,300 33,900	32,300	36.000 31,500 35,600	34,400	64,200 61,100 65,300	63,500	30.8 32.5 30.5	31.3	56.1 58.0 58.1	57.4
A5B5-1 -2 -3	34,400 31,200 36,000	33,900	36,800 33,600 37,500	36,000	65,200 61,600 66,000	64,300	29.9 33.0 30.5	31.1	55.1 61.0 54.4	56.8
A6B6-1 -2 -3	37,600 34,200 39,500	37,100	39,300 36,300 41,500	39,000	65,400 62,200 66,100	64,600	28.9 31.2 29.1	29.7	55.5 58.7 56.7	57.0
BR1BR2-1 -2 -3	33,700 32,300 34,400	33,500	35,700 33,800 36,400	35,300	64,700 66,400 65,000	65,400	30.7 29.0 30.3	30.0	55.3 37.8 52.9	48.7
Grand Avg		34,400		36,600		65,500		29.7		56.8
Mill Test				40,700		65,000		28.0		

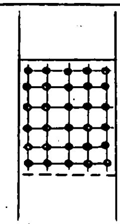
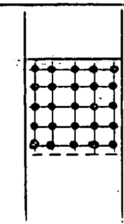
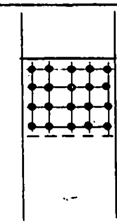
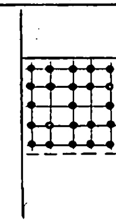
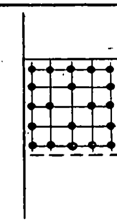
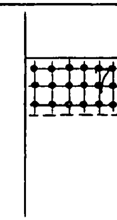
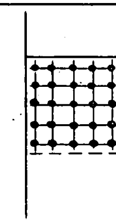
TABLE 5

RESULTS OF COUPON TESTS
(7/8" RIVETS)

Test No.	Static Yield Level psi	0.2 Offset Yield Stress psi	Ultimate Stress psi	Percent Elong. in 2" %	Percent Reduction in Area %
1	47,250	48,100	55,350	34.0	69.3
2	46,000	47,000	53,500	35.5	68.8
3	46,750	48,000	54,900	35.0	69.8
Avg.	46,700	47,700	54,600	34.8	69.3
Mill		41,400	57,000	33.5 in 8"	58.1
ASTM		28,000 Min.	52,000 62,000	24.0 in 8"	

TABLE 6

RESULTS OF B SERIES TESTS

	Units	B1	B2	B3	B4	B5	B6	BR2
Pattern								
Number of 7/8" A325 Bolts		30	25	20	23	20	18	25-7/8" A141 Rivets
Nominal Gross Area	sq in	36.0	36.0	36.0	36.0	36.0	36.0	36.0
Nominal Net Area	sq in	26.6	26.6	26.6	26.6	26.6	24.8	26.6
Nominal Shear Area	sq in	36.1	30.0	24.0	27.7	24.0	21.6	30.0
Tension: Shear Ratio		1:0.74	1:0.89	1:1.11	1:0.96	1:1.11	1:1.15	1:0.89
Slip Load	kips	1238	1047	911	850	609	673	654
Nominal Bolt Shear	ksi	34.3	34.9	38.0	30.7	25.4	31.2	21.8
Tension on Net Section	ksi	46.5	39.4	34.2	32.0	22.9	27.1	24.6
Avg. Extension of Bolts	in	0.0451	0.0457	0.0461	0.0358	0.0367	0.0357	
Initial Clamping Force	kips	1451	1211	969	1089	949	852	
Coefficient of Friction		0.427	0.432	0.465	0.390	0.321	0.395	
Ultimate Load	kips	1956	1948	1750	1786	1680	1550	1300
Nominal Bolt Shear	ksi	54.2	64.9	72.9	64.5	70.0	71.8	43.3
Tension on Net Section	ksi	73.5	73.2	65.8	67.1	63.2	62.5	48.9
Type of Failure		Tear at net sect-main plate	Tear at net sect-1 lap plate	Shear of bolts	Tear at net sect-1 lap plate	Shear of bolt	Shear of bolt	Shear of rivets
Efficiency, gross		82.8	82.5		75.6			
Efficiency, net		107.3	110.4		105.6			

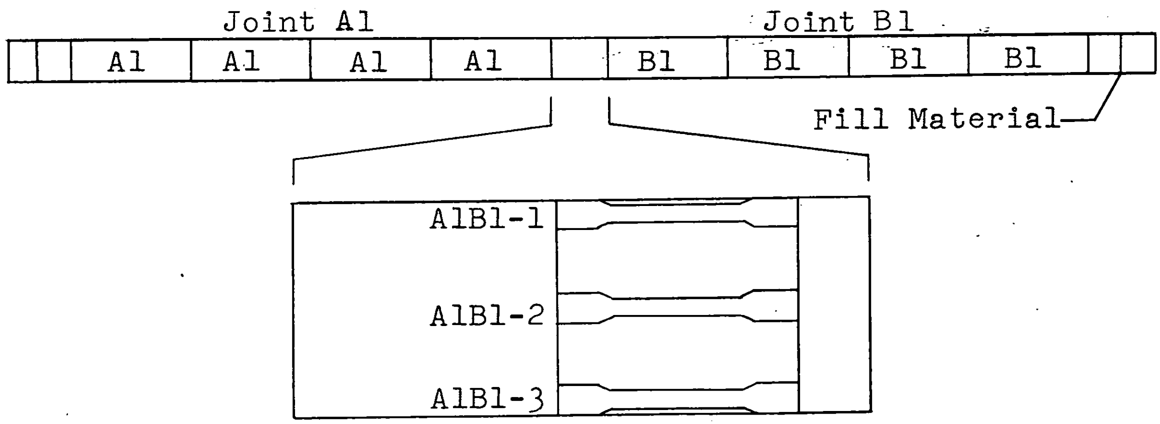


Fig. 1 LOCATION OF COUPONS

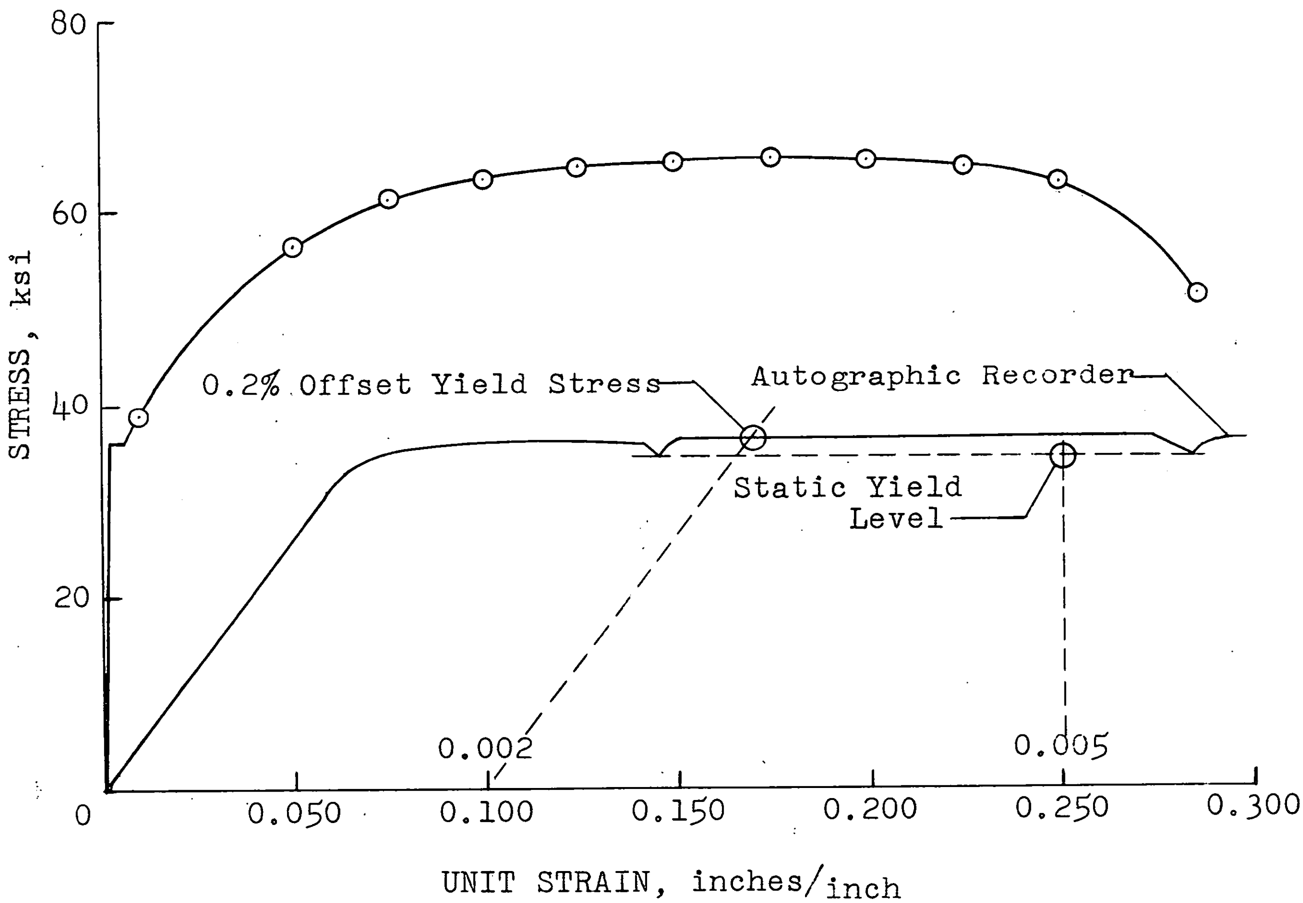


Fig. 2 STRESS vs STRAIN FOR PLATE MATERIAL COUPONS CUT FROM 1" x 18" U.M. A7 STEEL

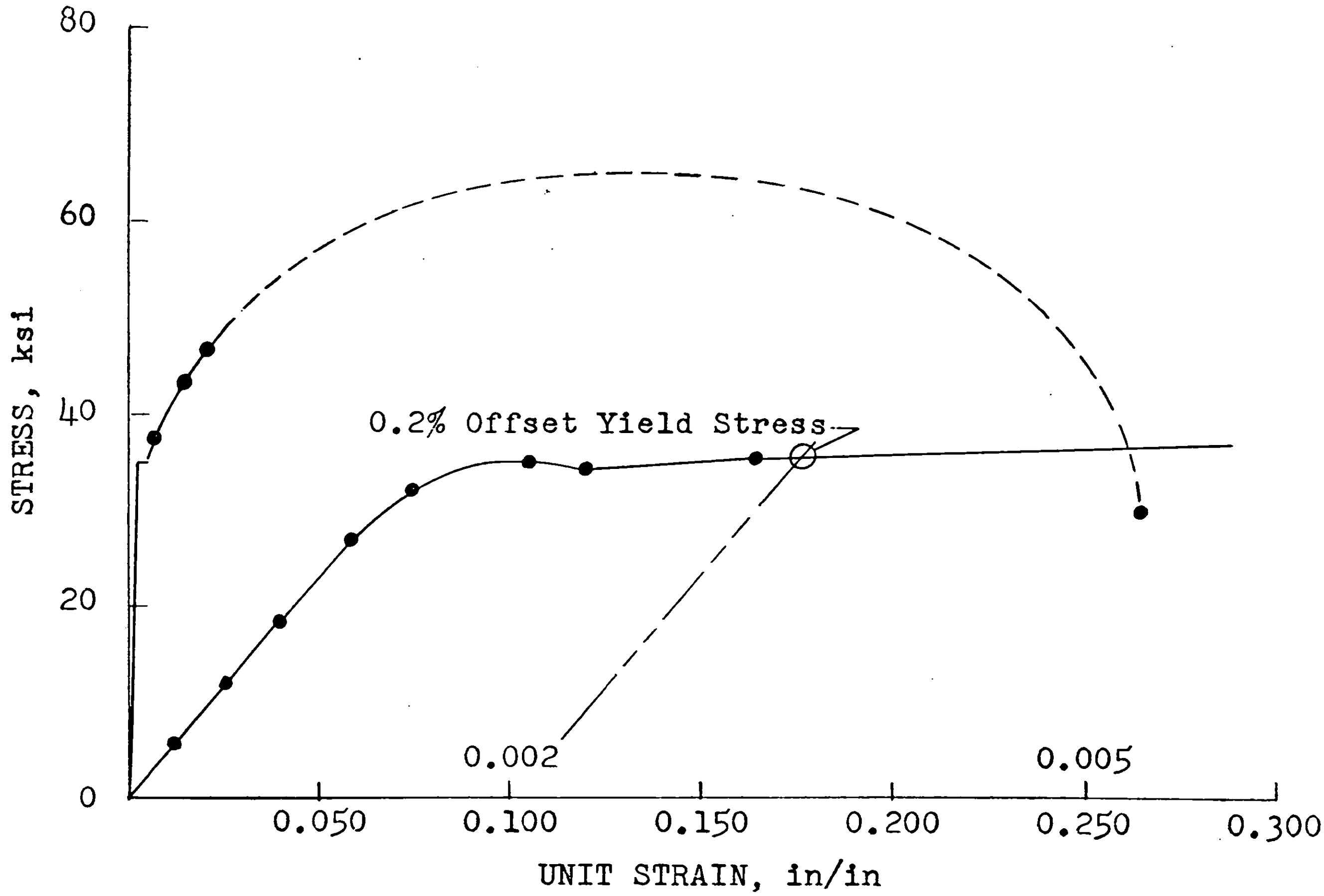


FIG. 3. STRESS VS. STRAIN FOR "PI" DOUBLE PLATE "COUPON"

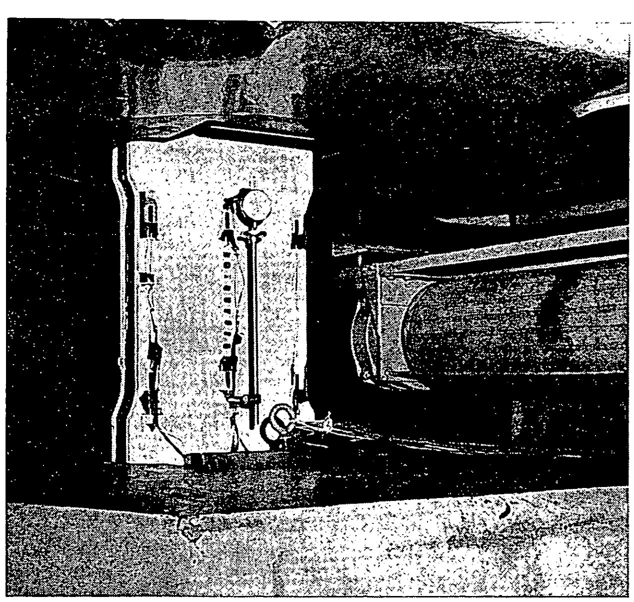


FIG. 4. "PI COUPON" TEST SET-UP

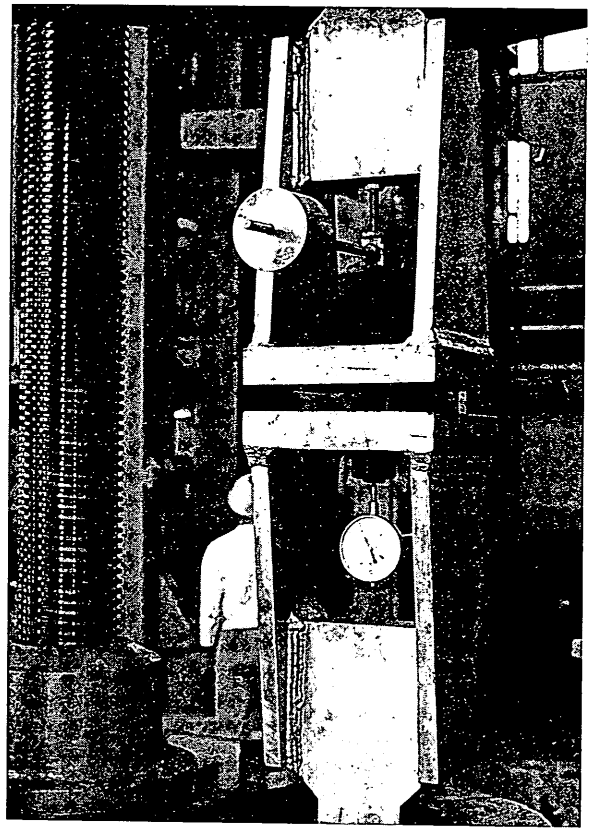


FIG. 5. BOLT CALIBRATION SET-UP

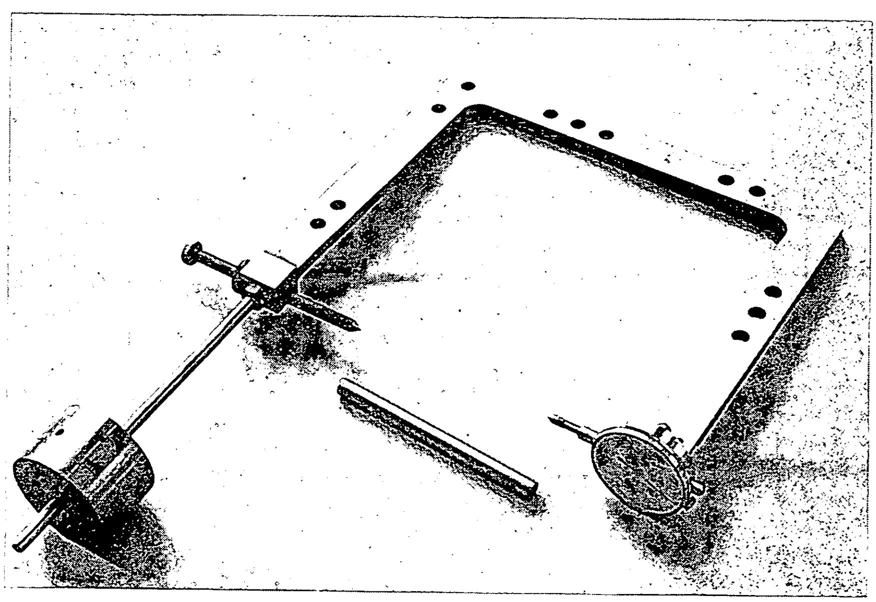


FIG. 6. BOLT EXTENSOMETER AND ZERO BAR

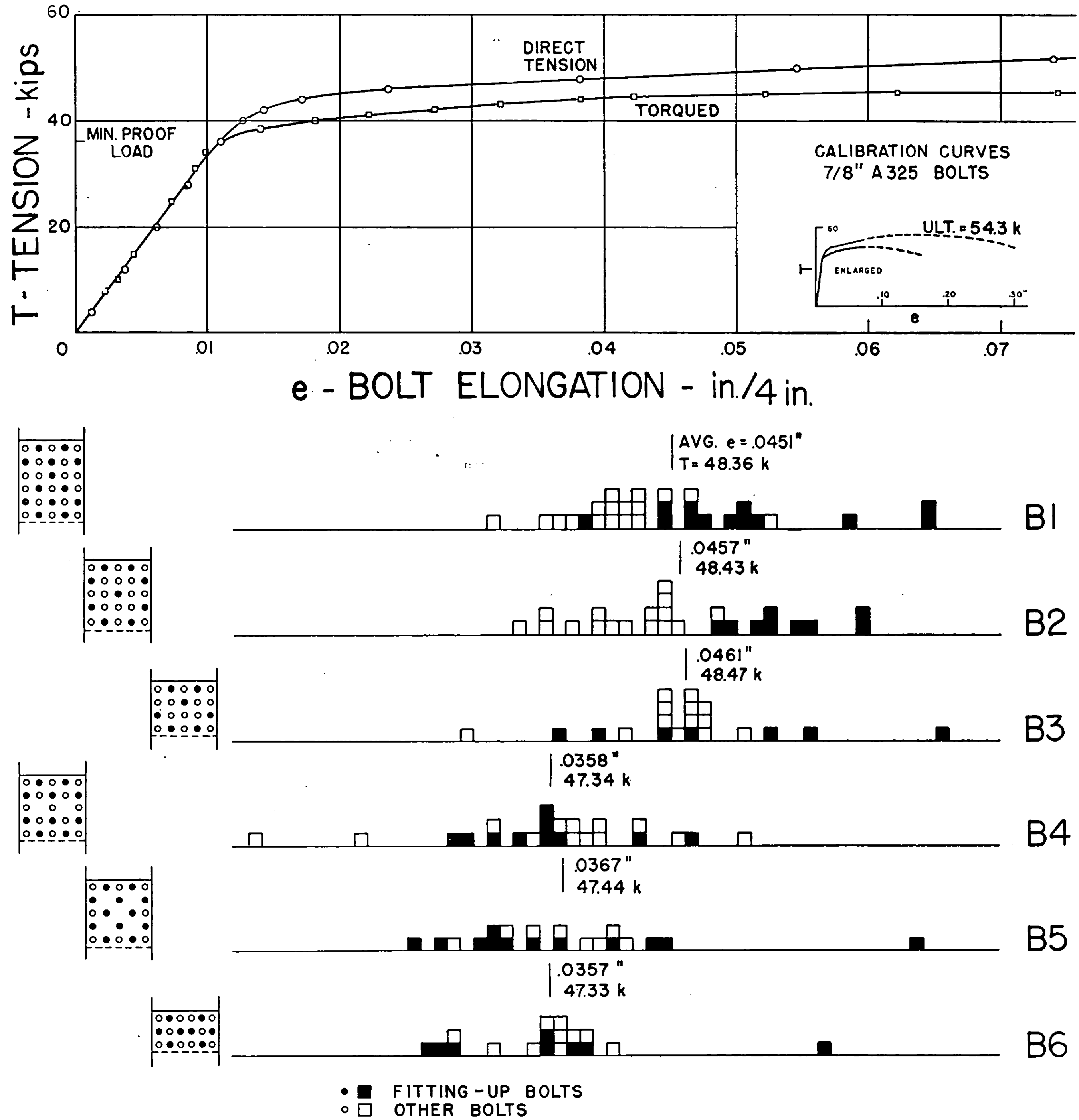


Fig.7 BOLT TENSION DISTRIBUTION

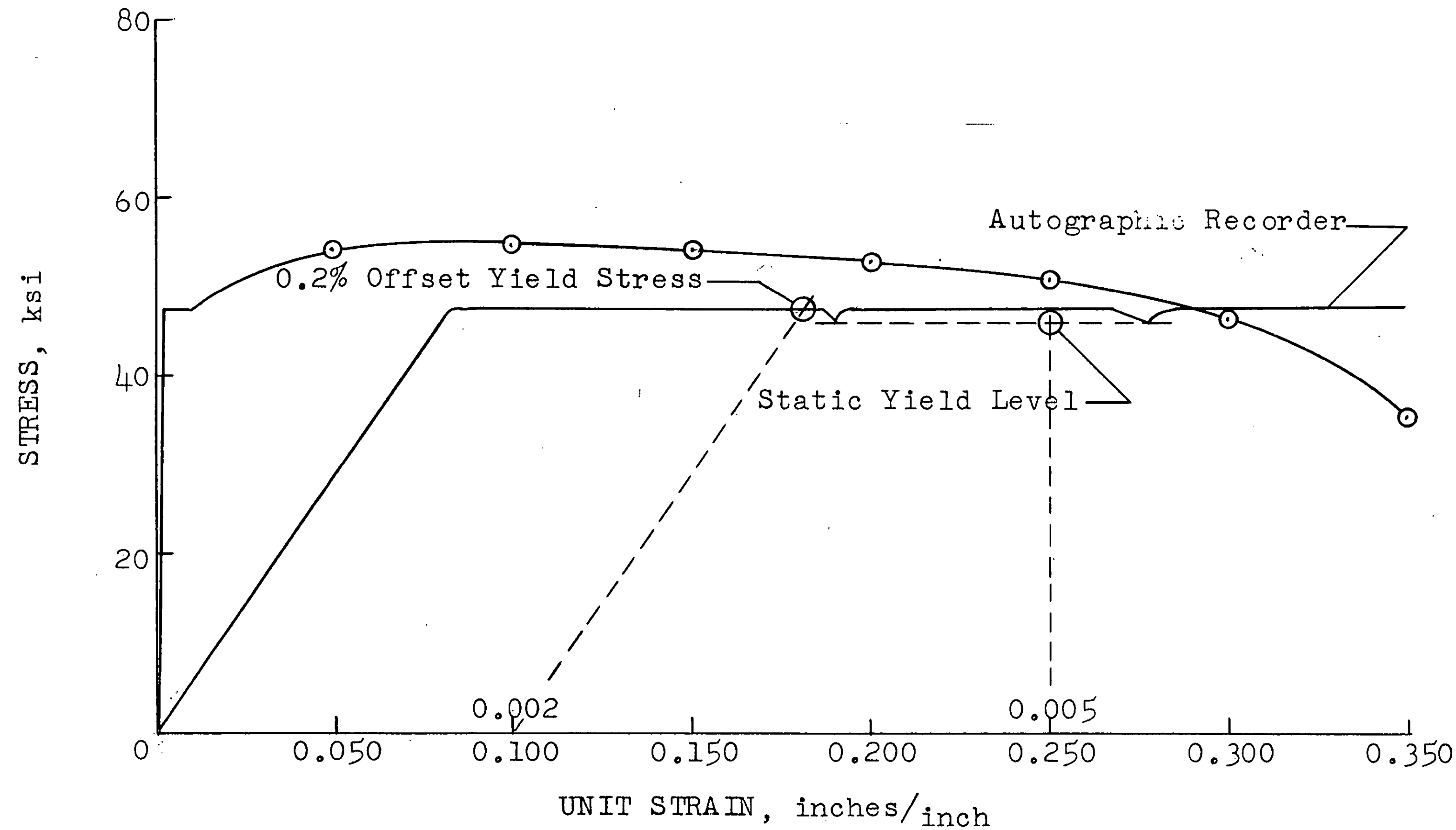


Fig. 8 STRESS vs STRAIN FOR RIVETS
0.505" DIAM. COUPONS CUT FROM 7/8" MFG. RIVETS

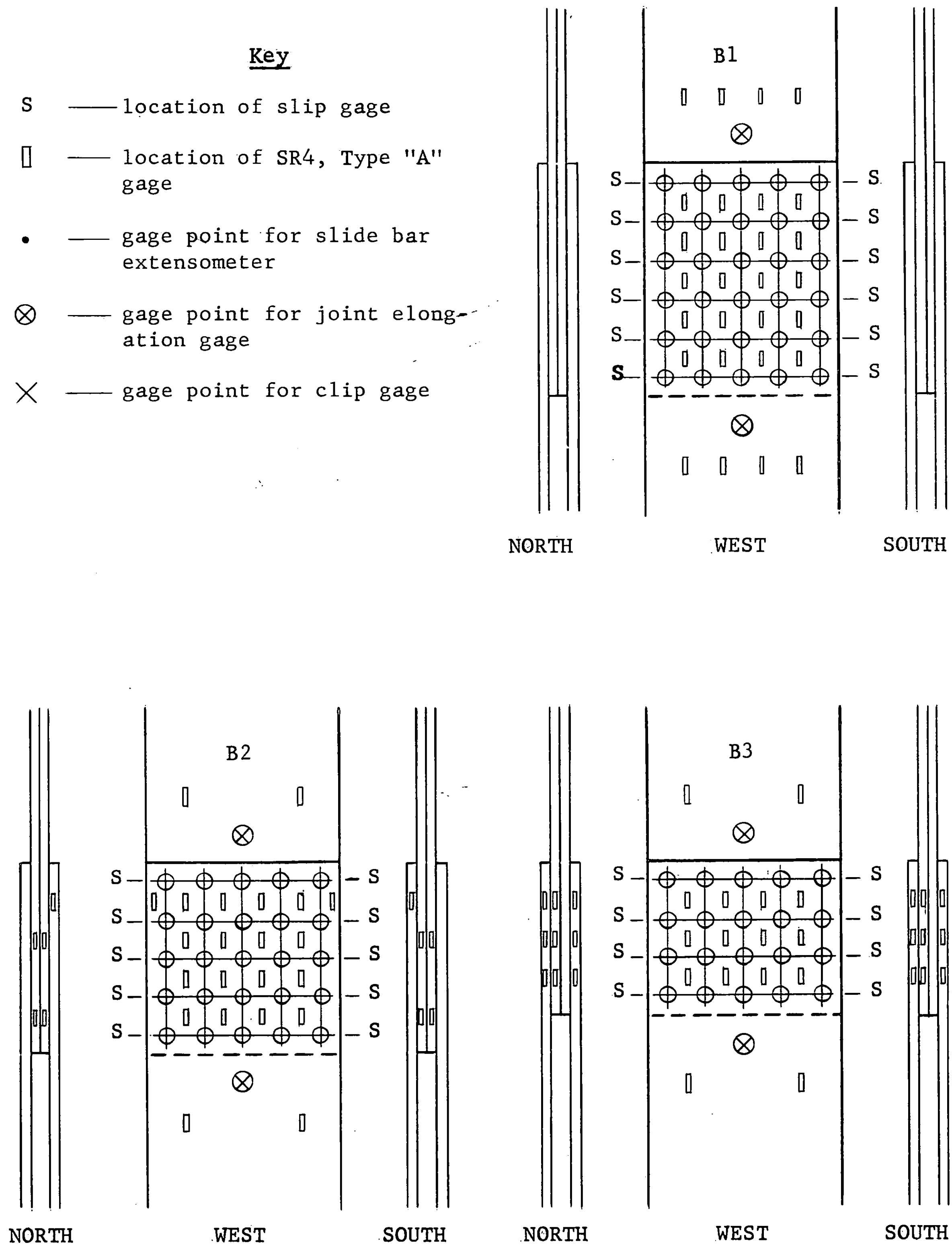


Fig 9 INSTRUMENTATION

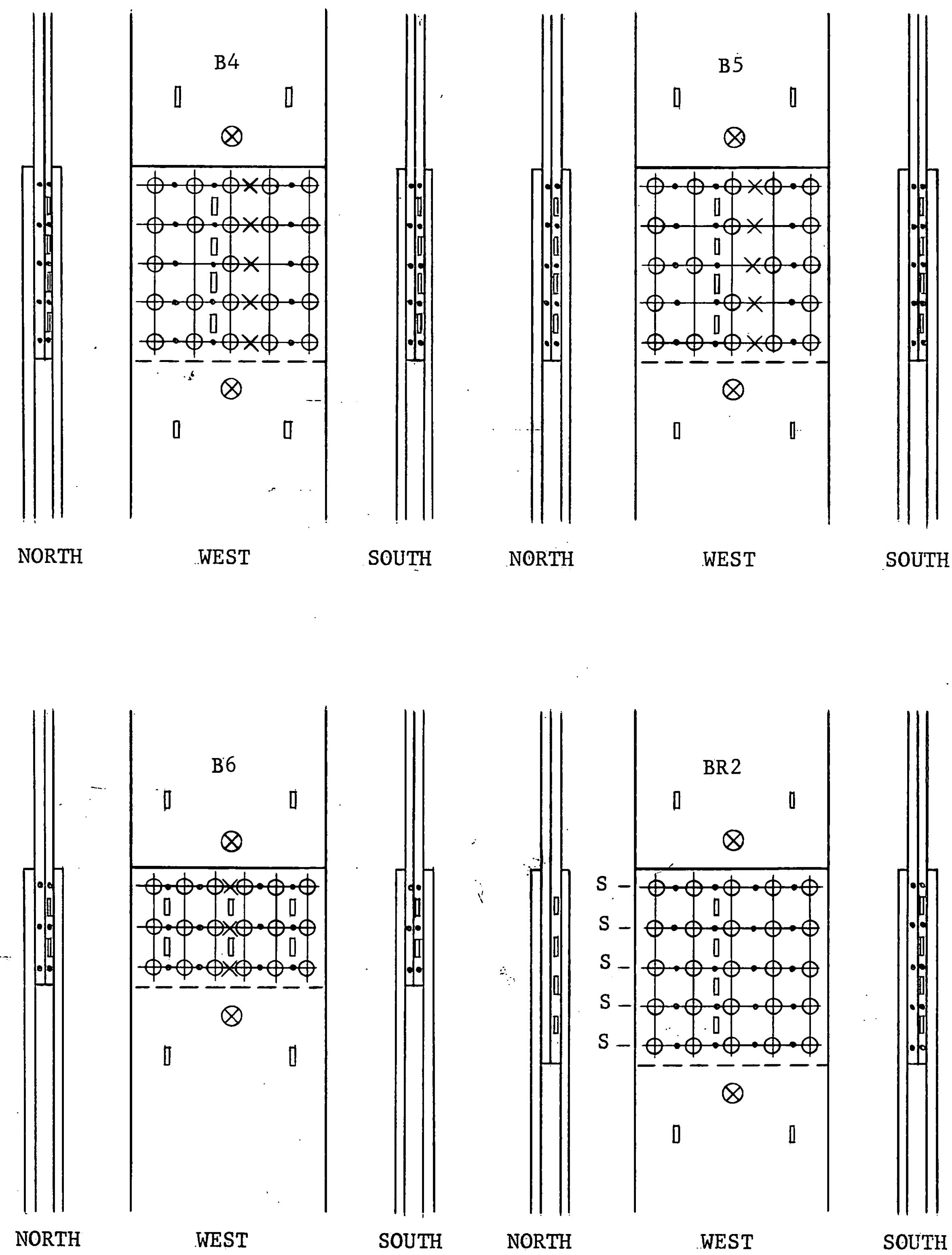


Fig 9 INSTRUMENTATION
(cont.)

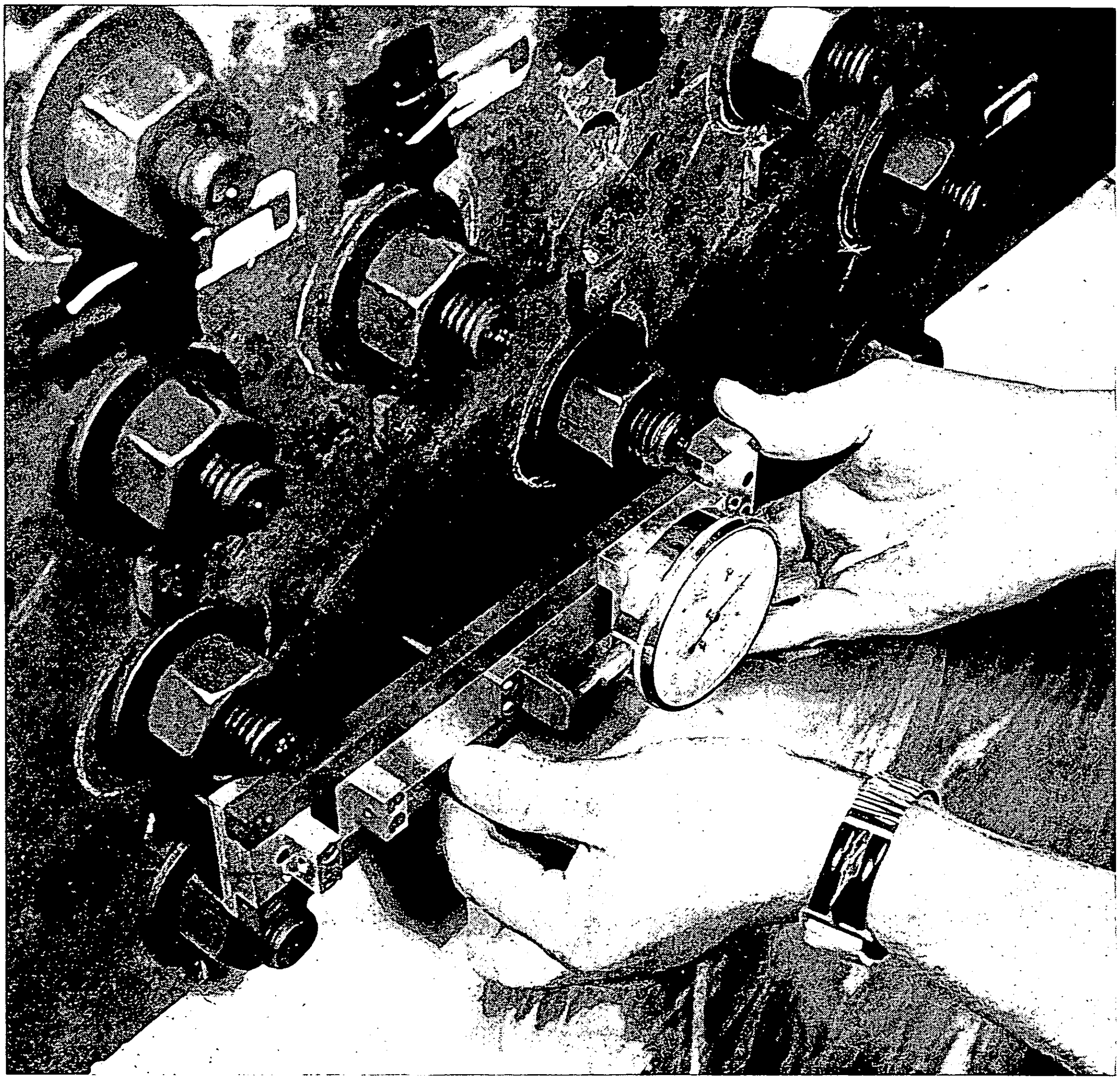


FIG. 10. SLIDE BAR EXTENSOMETER

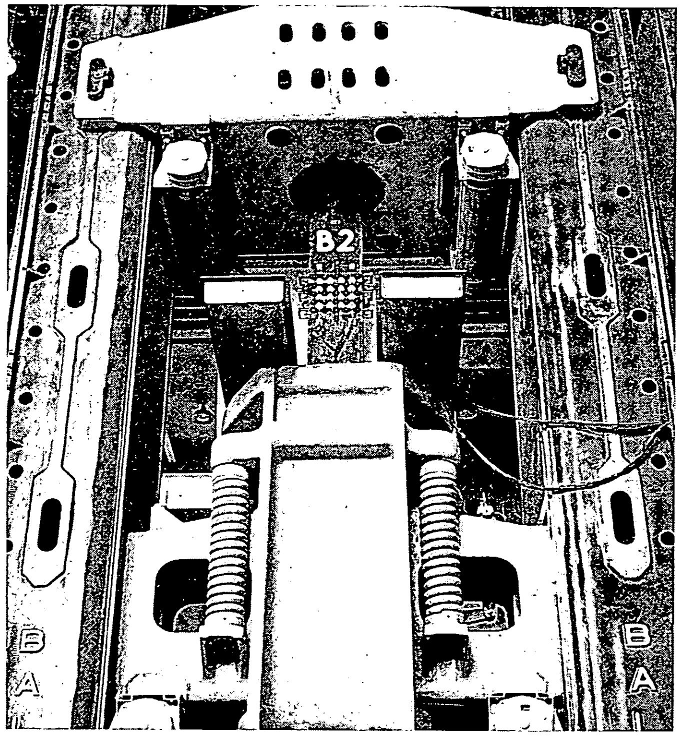


FIG. 11. GENERAL TEST SET-UP

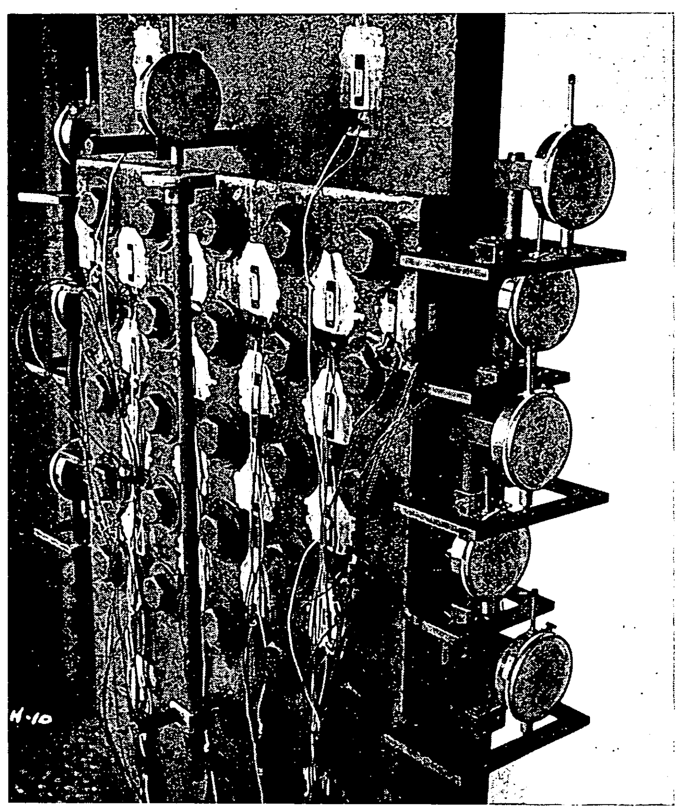


FIG. 12. INSTRUMENTATION

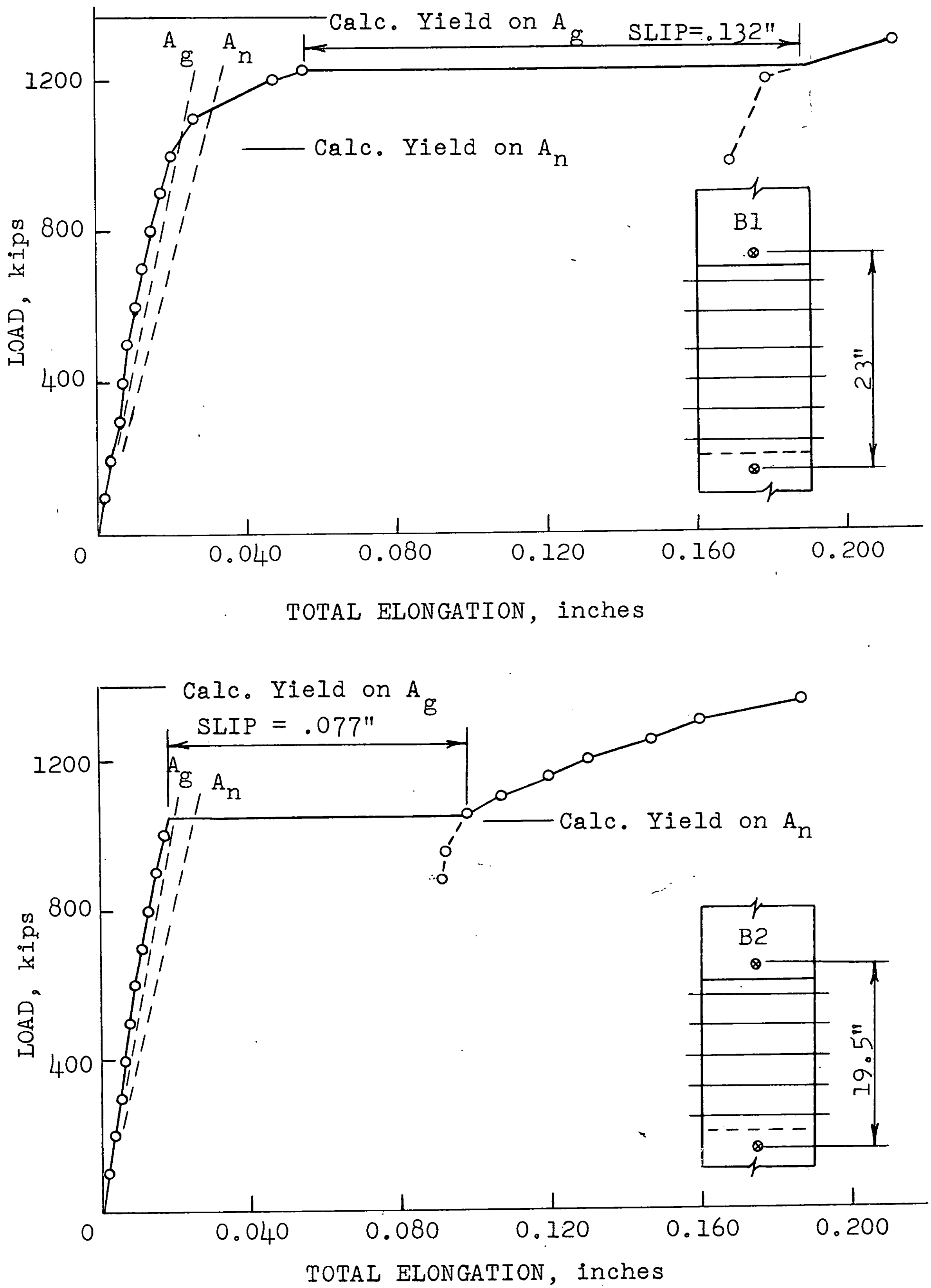
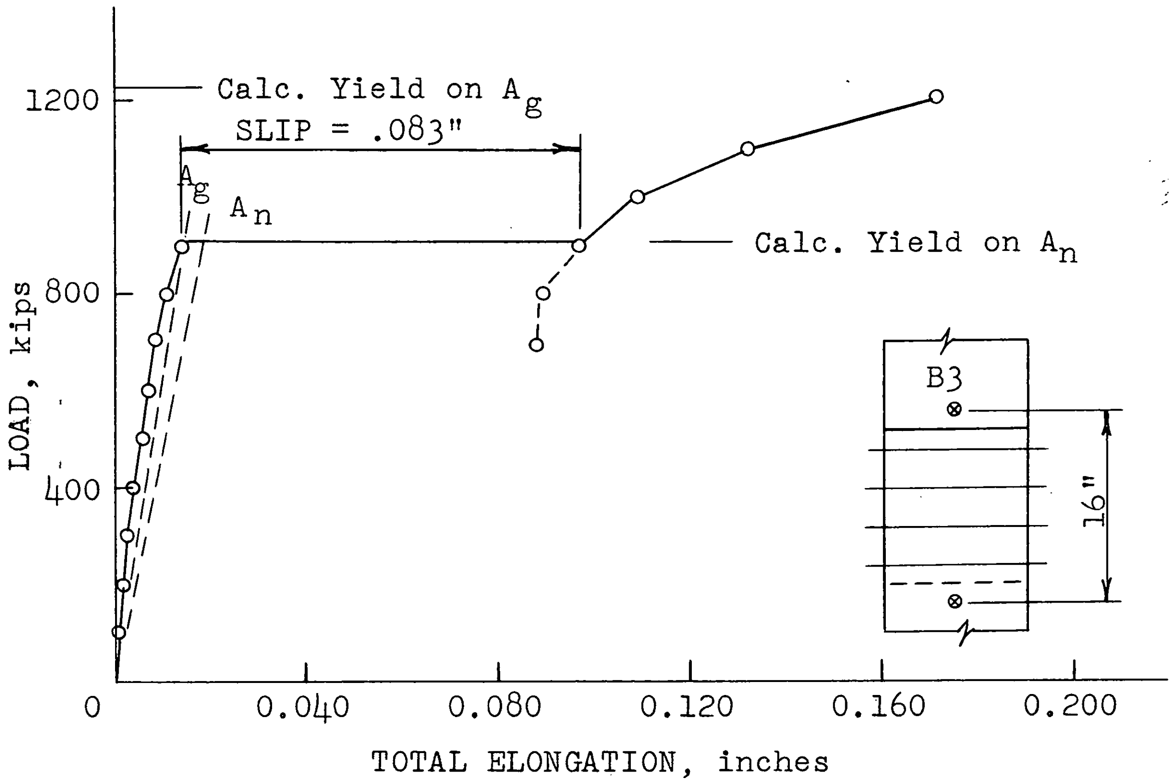


Fig. 13a,b LOAD vs TOTAL ELONGATION FOR JOINTS B1 AND B2



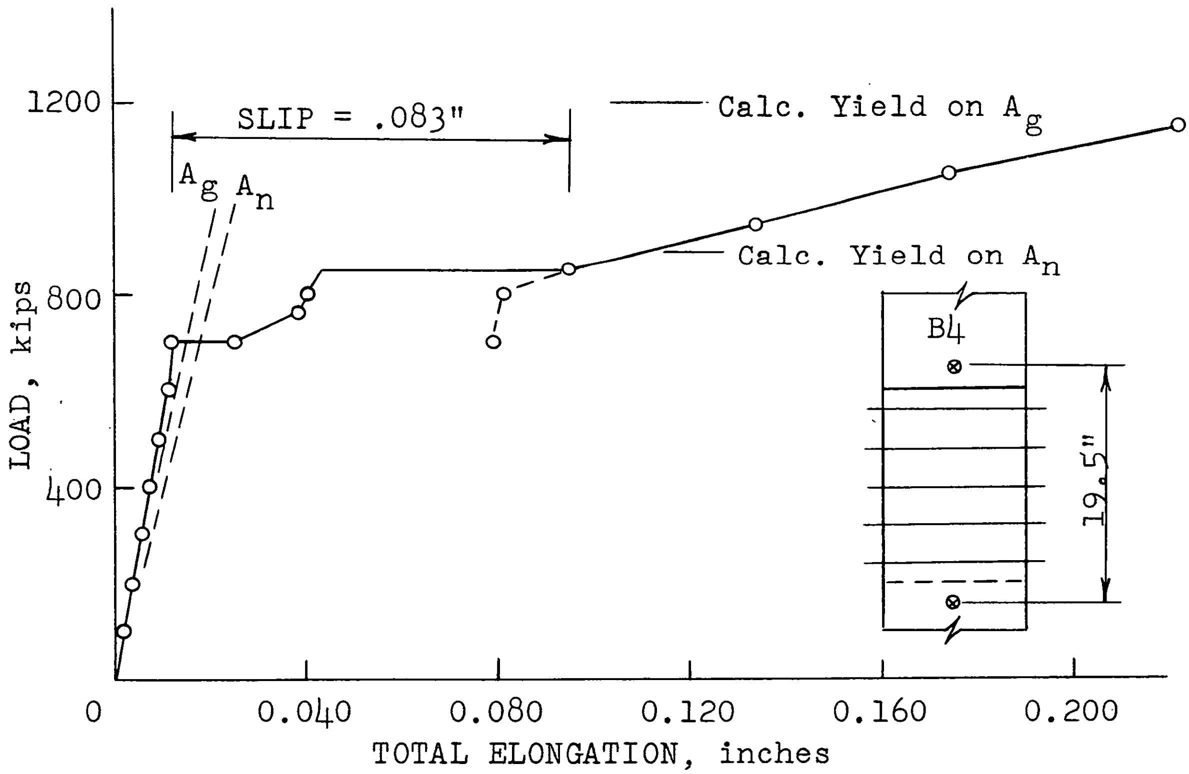
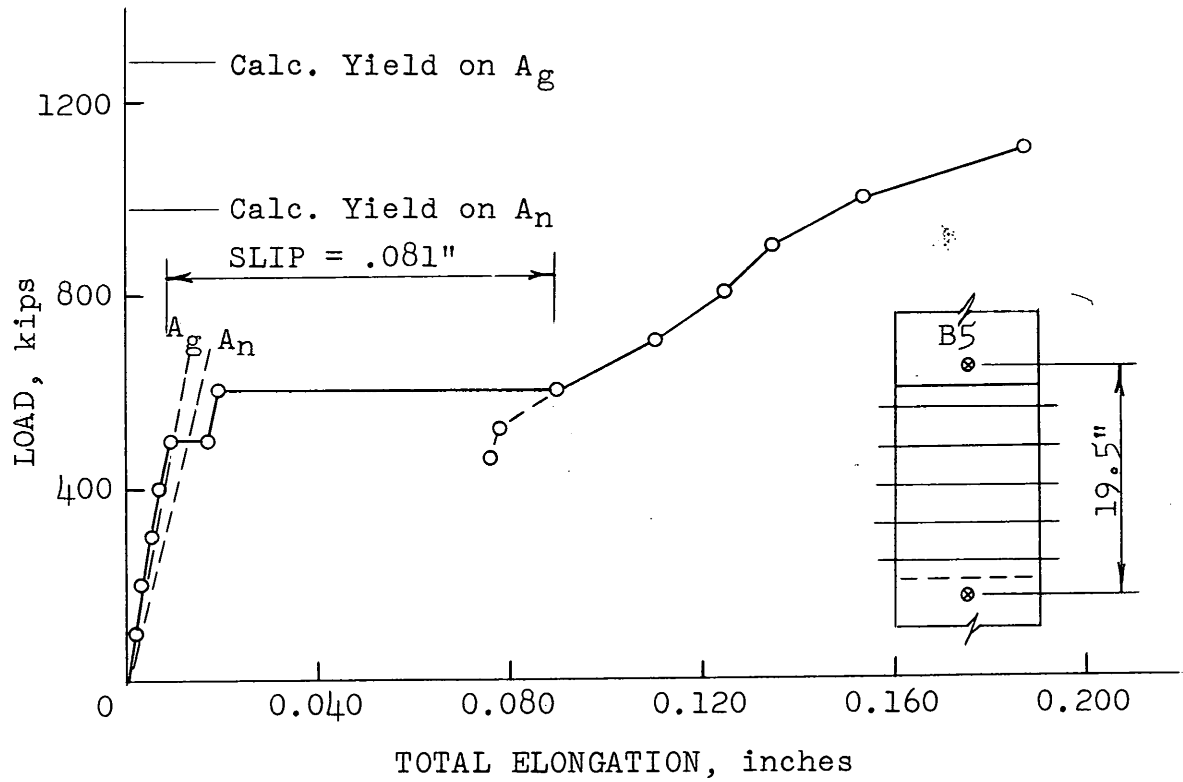


Fig. 13c,d LOAD vs TOTAL ELONGATION FOR JOINTS B3 AND B4



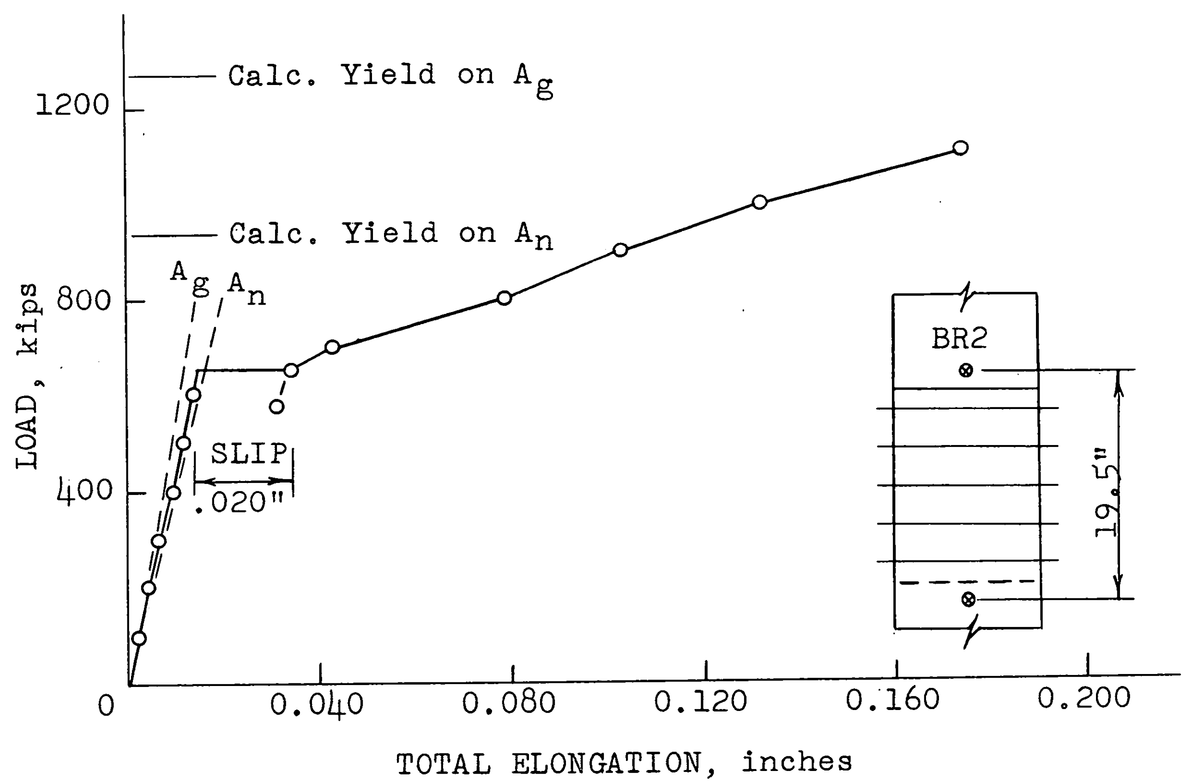


Fig. 13e,f LOAD vs TOTAL ELONGATION FOR JOINTS B5 AND BR2

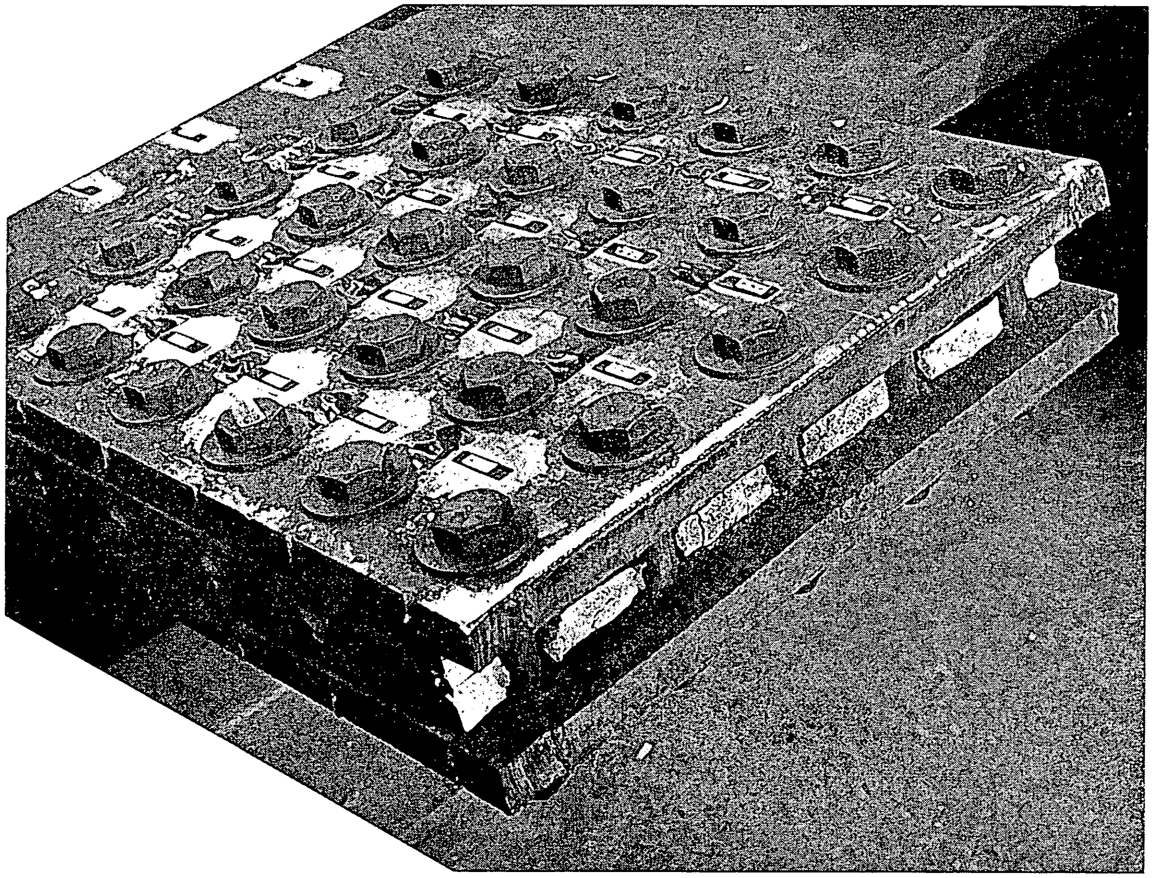


FIG. 14. TENSILE FAILURE OF JOINT B1

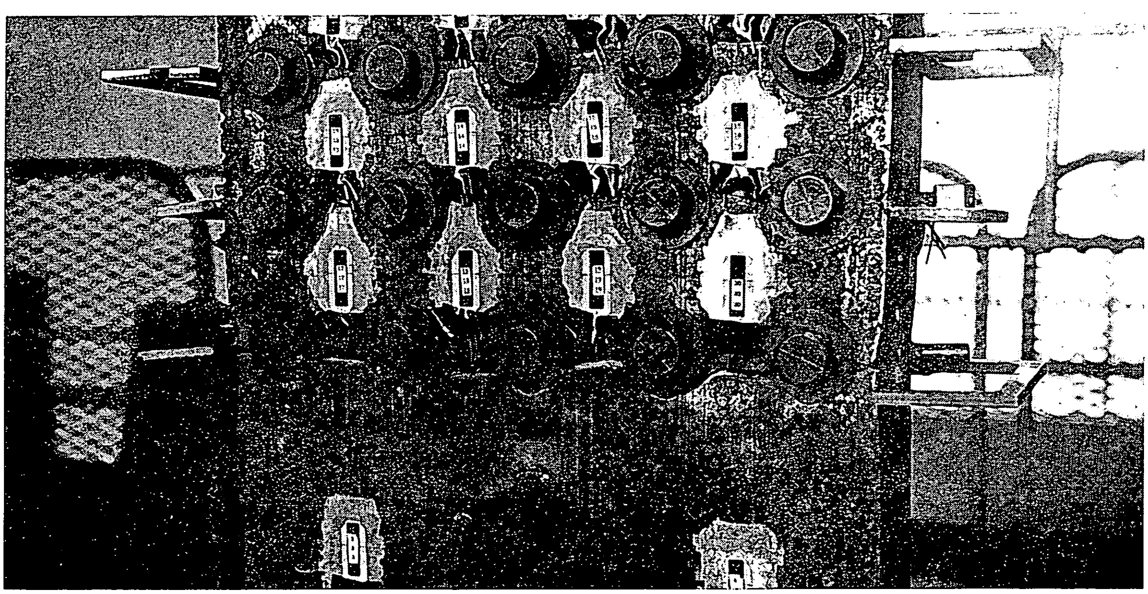


FIG. 15. TENSILE FAILURE OF JOINT B2

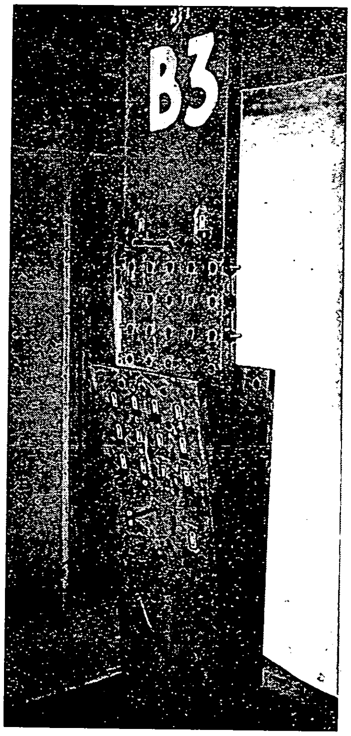


FIG. 16. SHEAR FAILURE OF JOINT B3

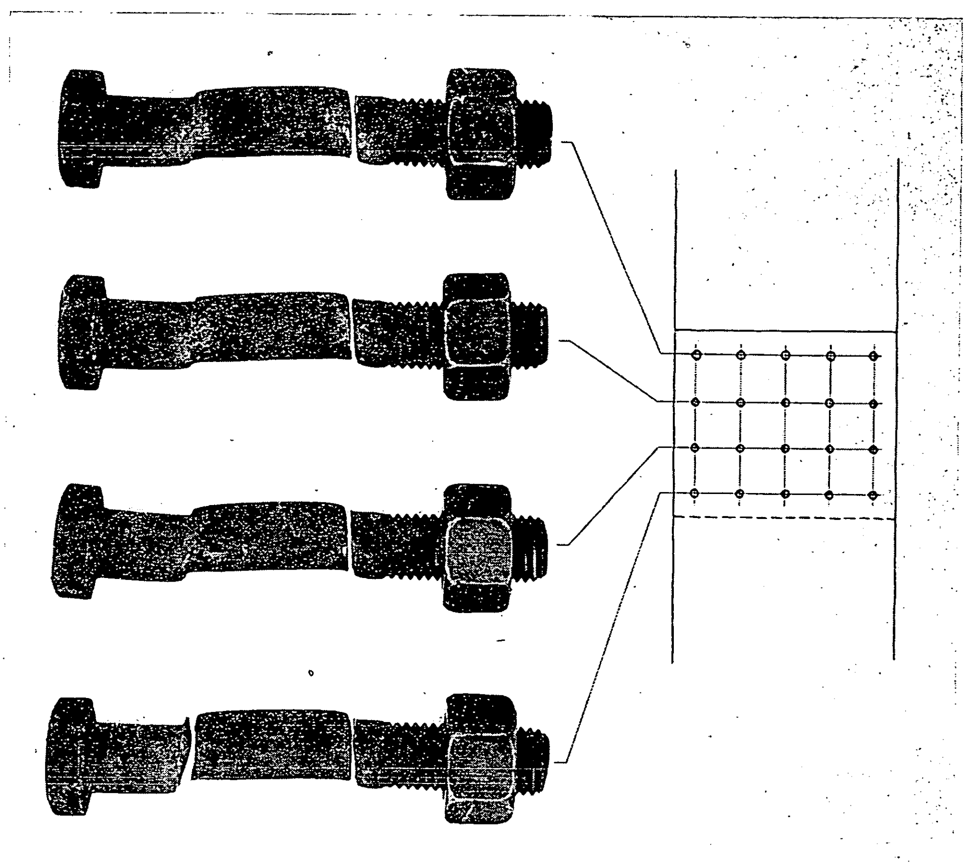


FIG. 17. BOLT FAILURES OF JOINT B3

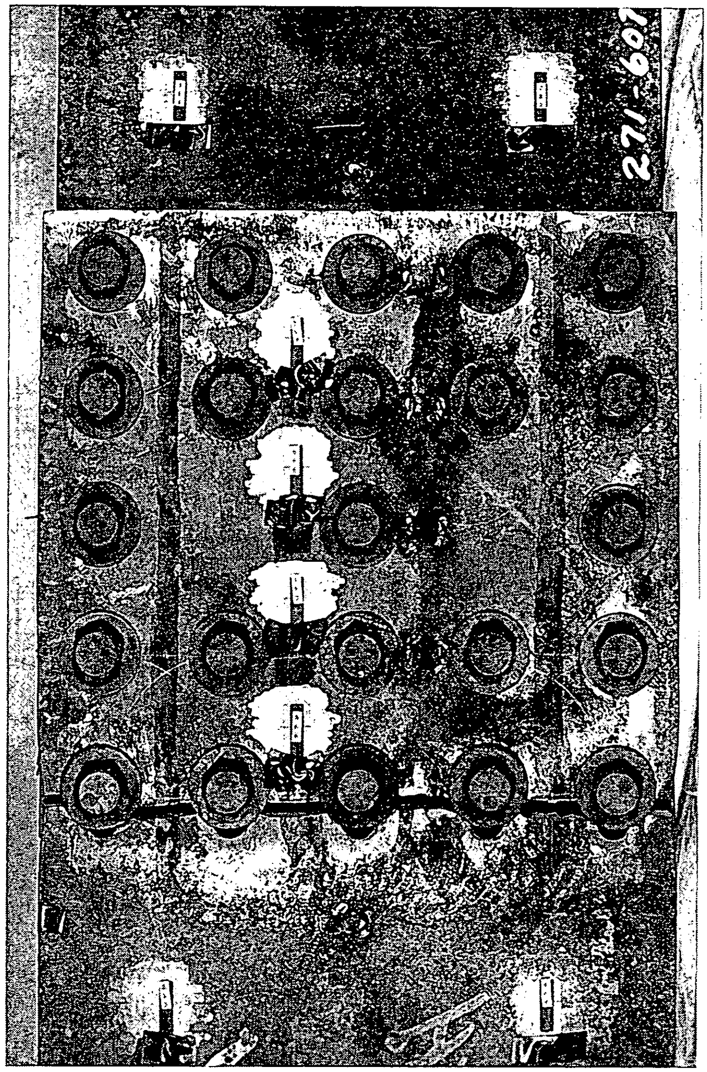


FIG. 18. TENSILE FAILURE OF JOINT B4

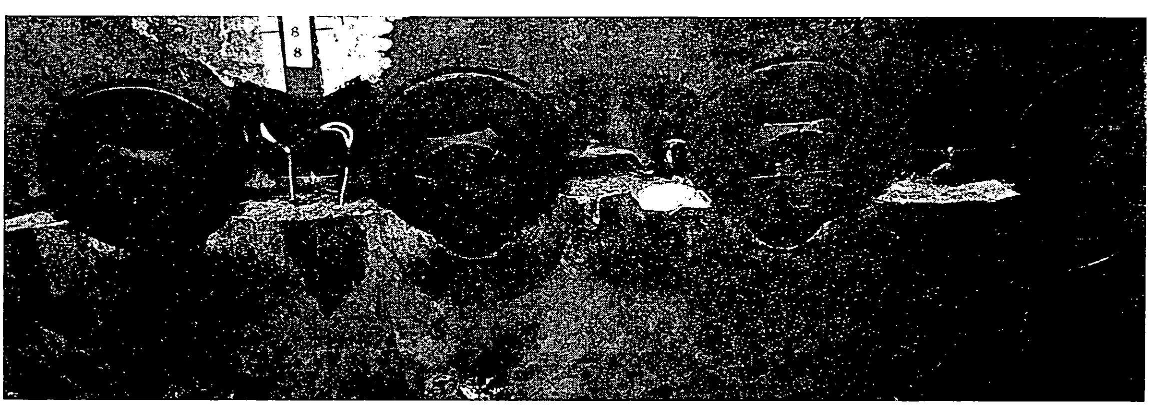


FIG. 19. CLOSE-UP OF TENSILE FAILURE OF JOINT B4

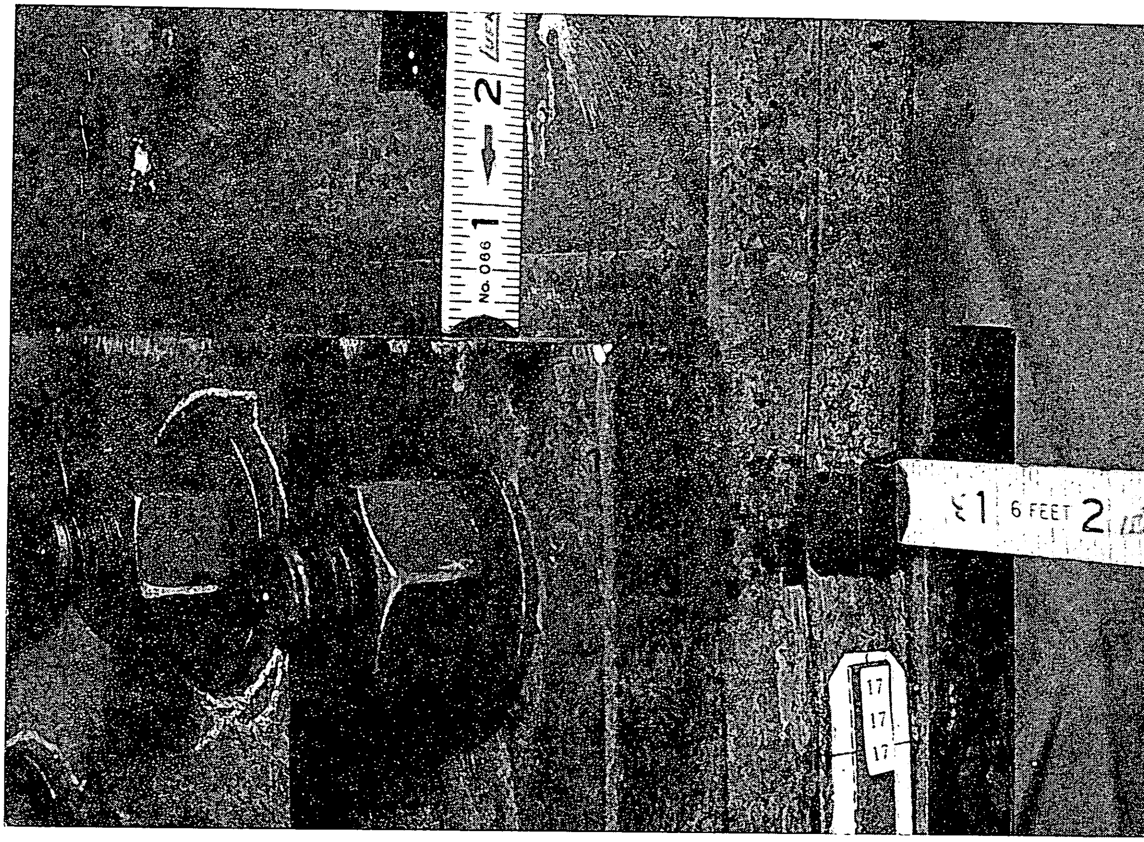


FIG. 20. JOINT B4 AFTER FAILURE SHOWING SLIP AND NECKING OF MAIN PLATES

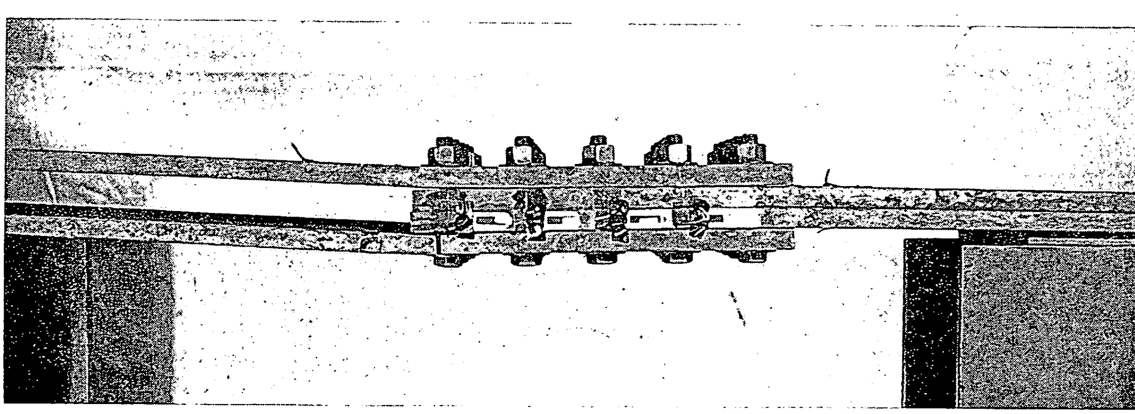


FIG. 21. EDGE VIEW OF JOINT B4 FAILURE SHOWING BENDING OF INTACT LAP PLATE

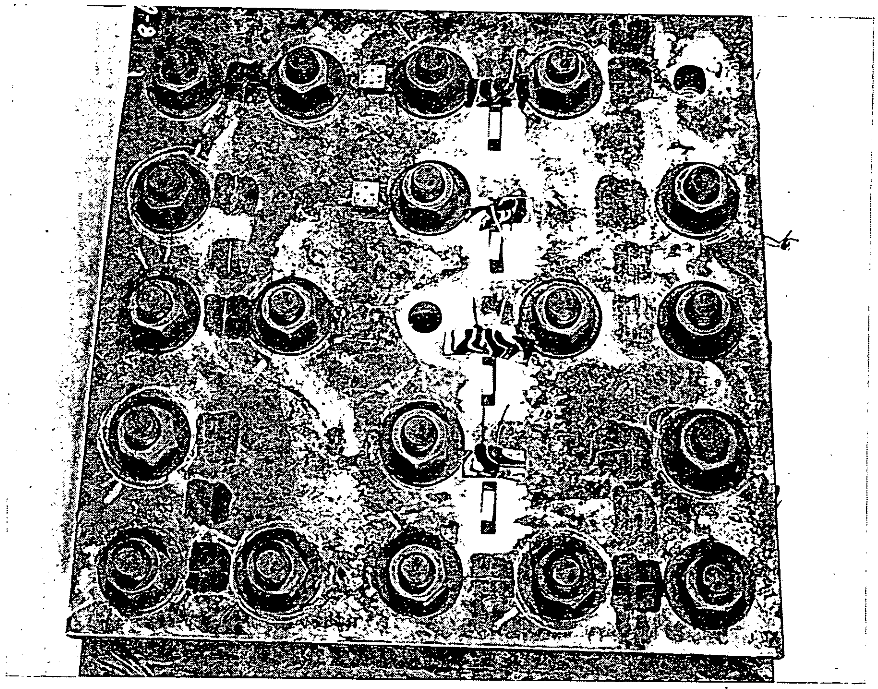


FIG. 22. SHEAR FAILURE OF JOINT B5

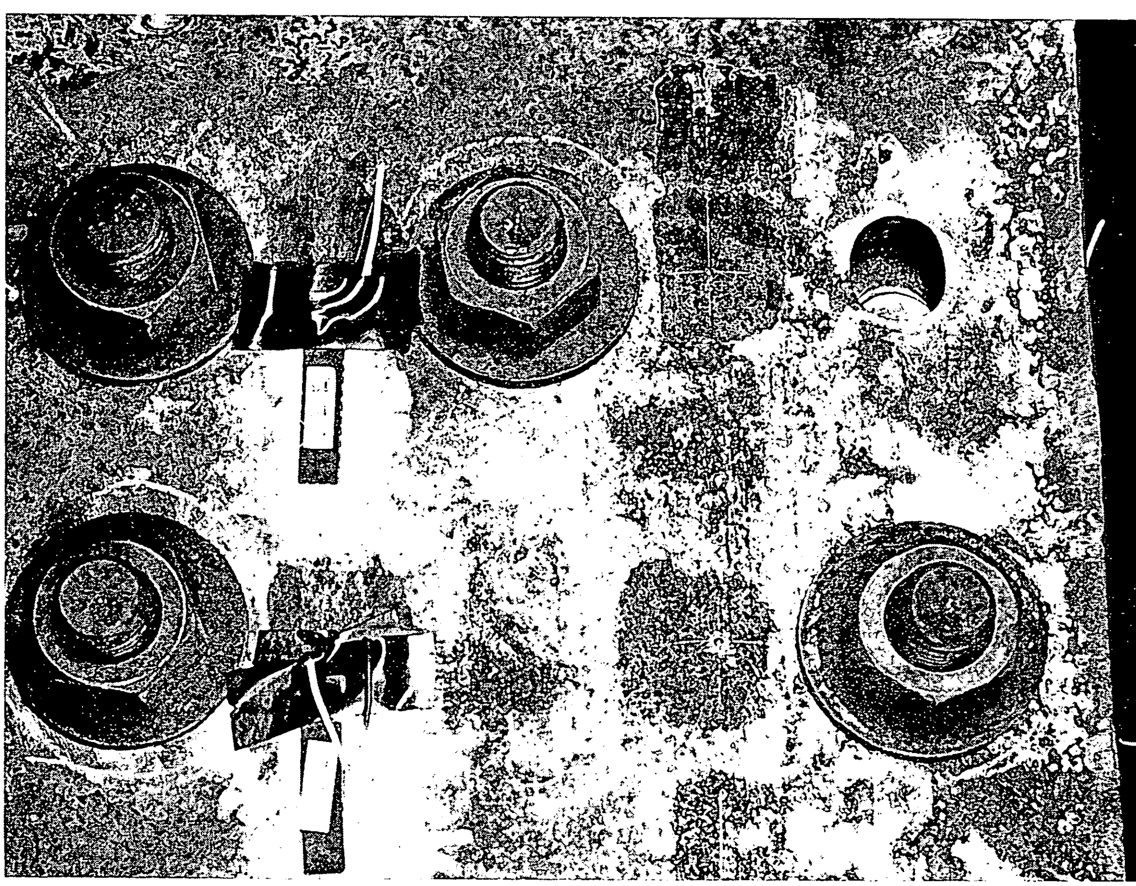


FIG. 23. JOINT B5 FAILURE SHOWING SHEARED BOLT SHANK
AND HOLE DEFORMATION

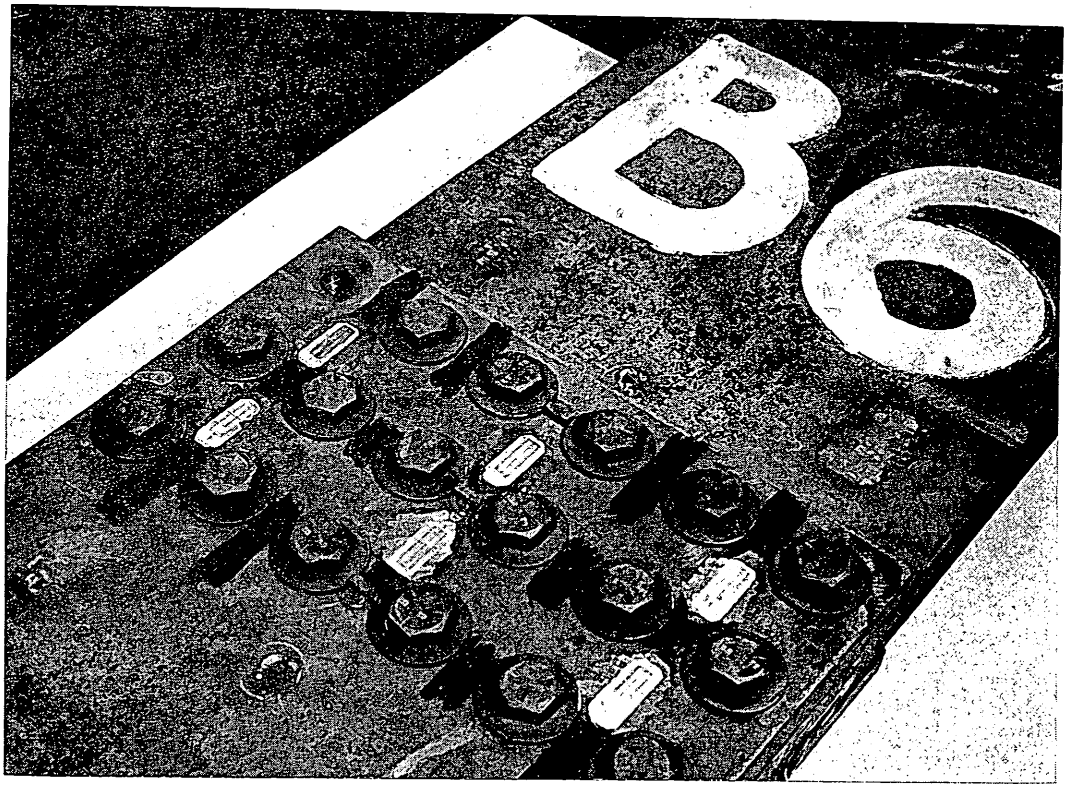


FIG. 24. SHEAR FAILURE OF JOINT B6

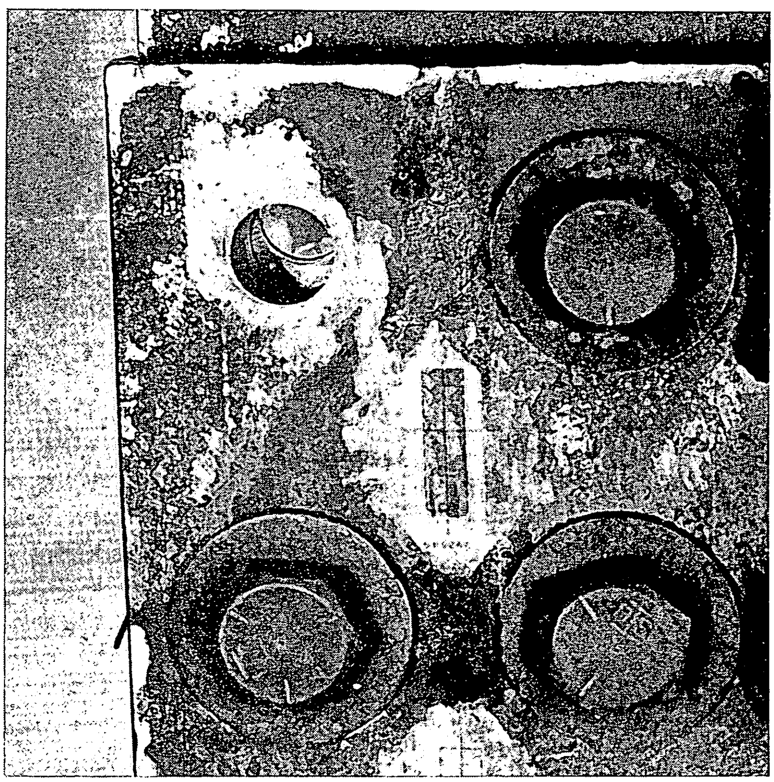


FIG. 25. JOINT B6 FAILURE SHOWING SHEARED BOLT SHANK

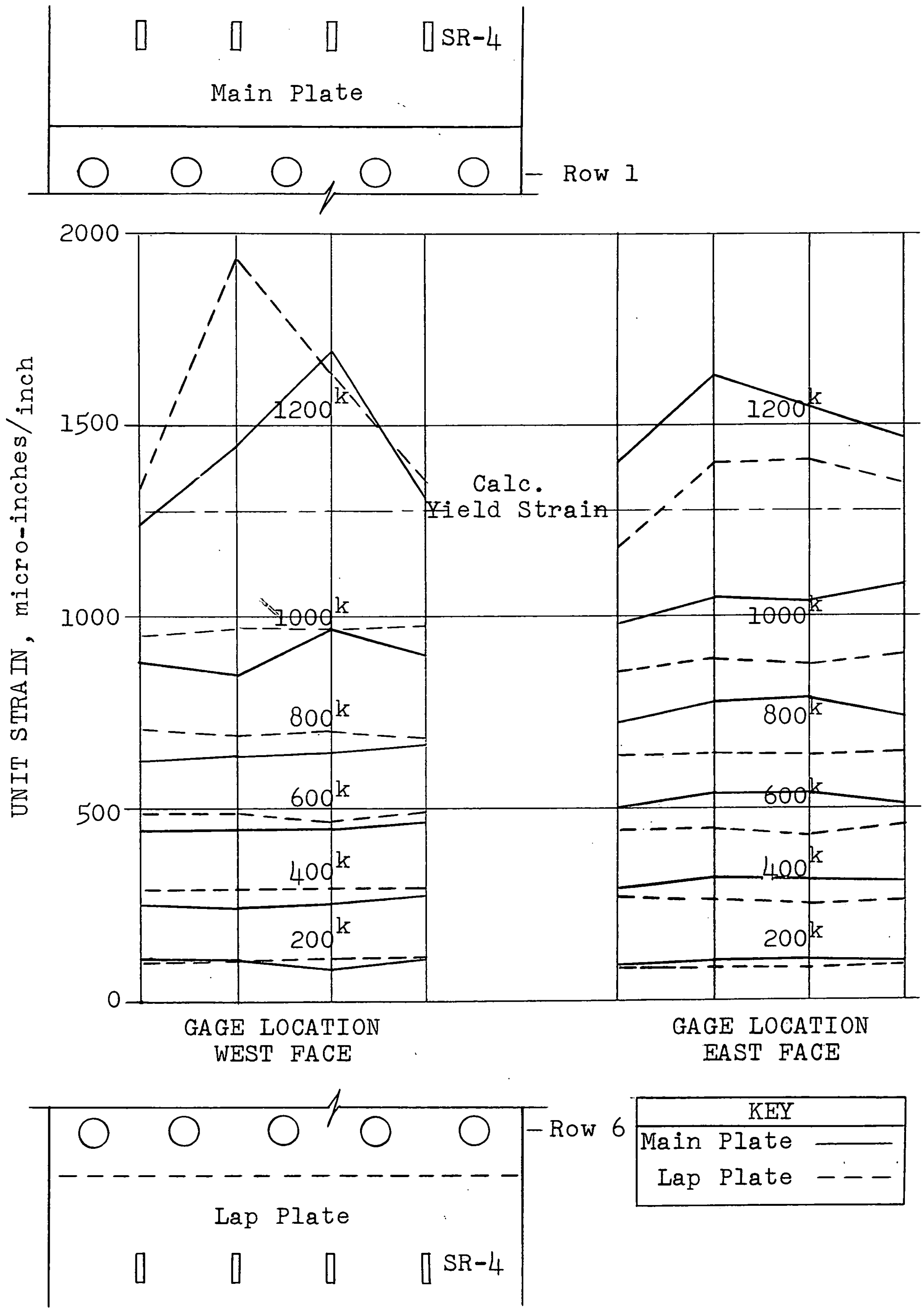
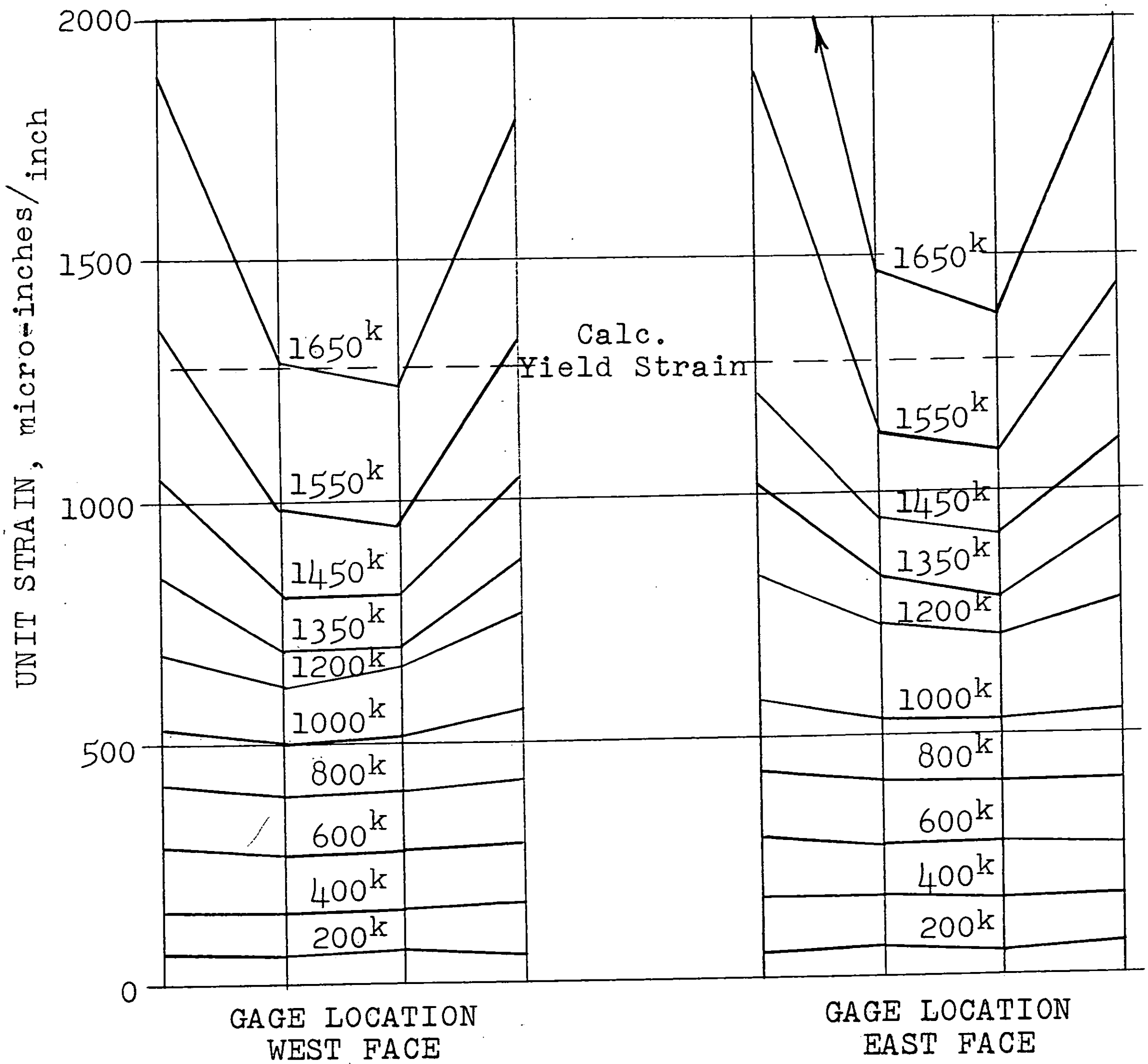


Fig. 26 STRAIN DISTRIBUTION FOR JOINT B1
GROSS SECTION



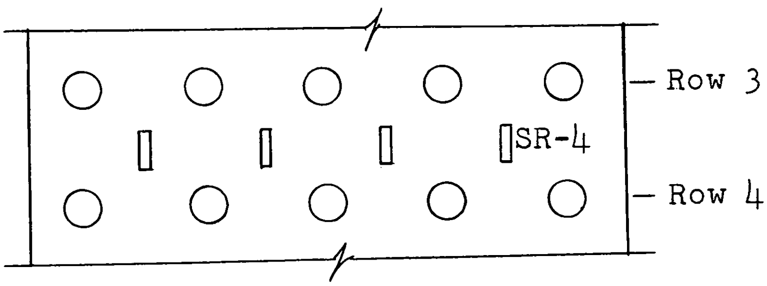


Fig. 27 STRAIN DISTRIBUTION FOR JOINT B1, HORIZONTAL CENTERLINE OF BOLT GROUP

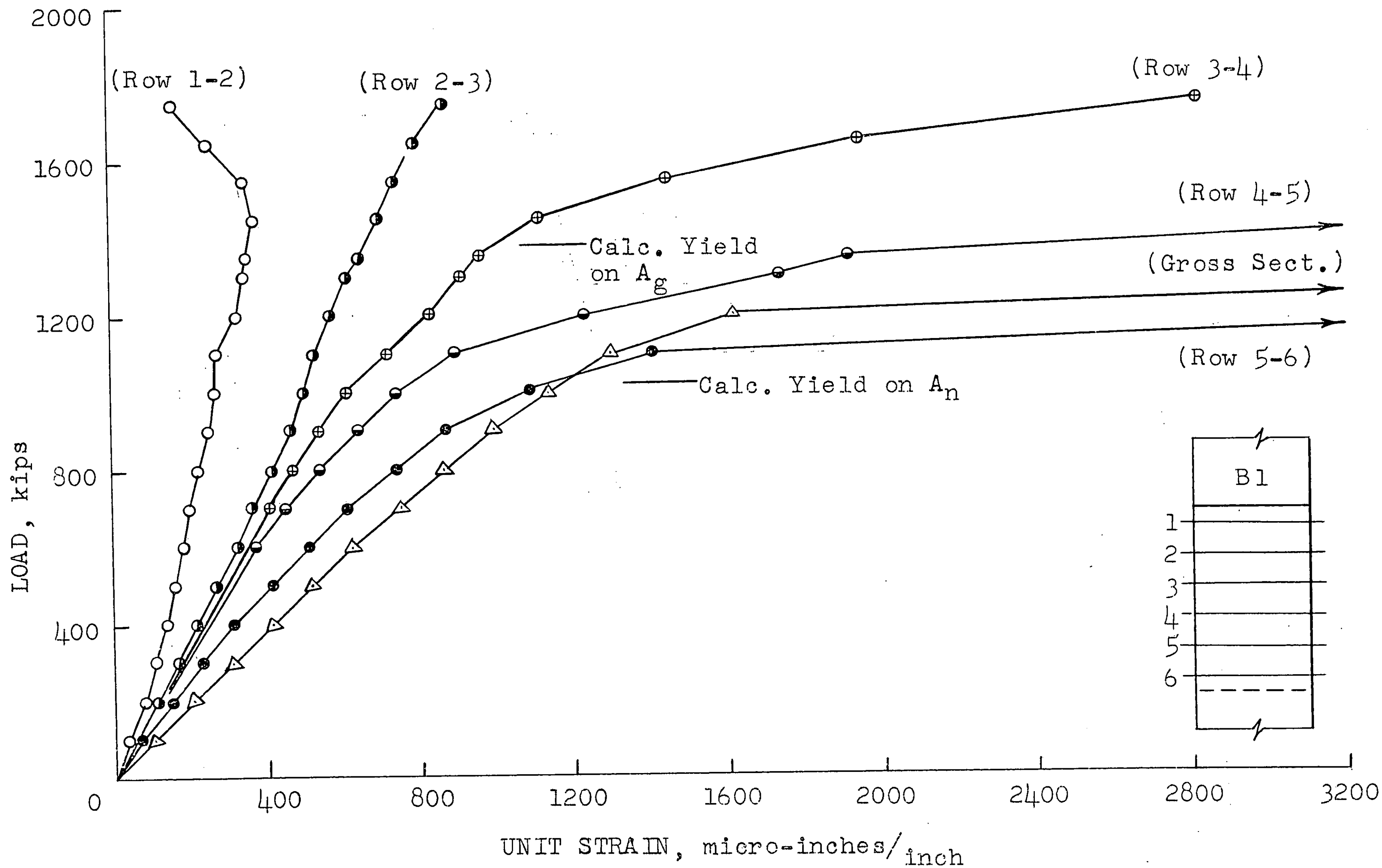


Fig. 28 LOAD vs STRAIN FOR EAST LAP PLATE OF JOINT B1

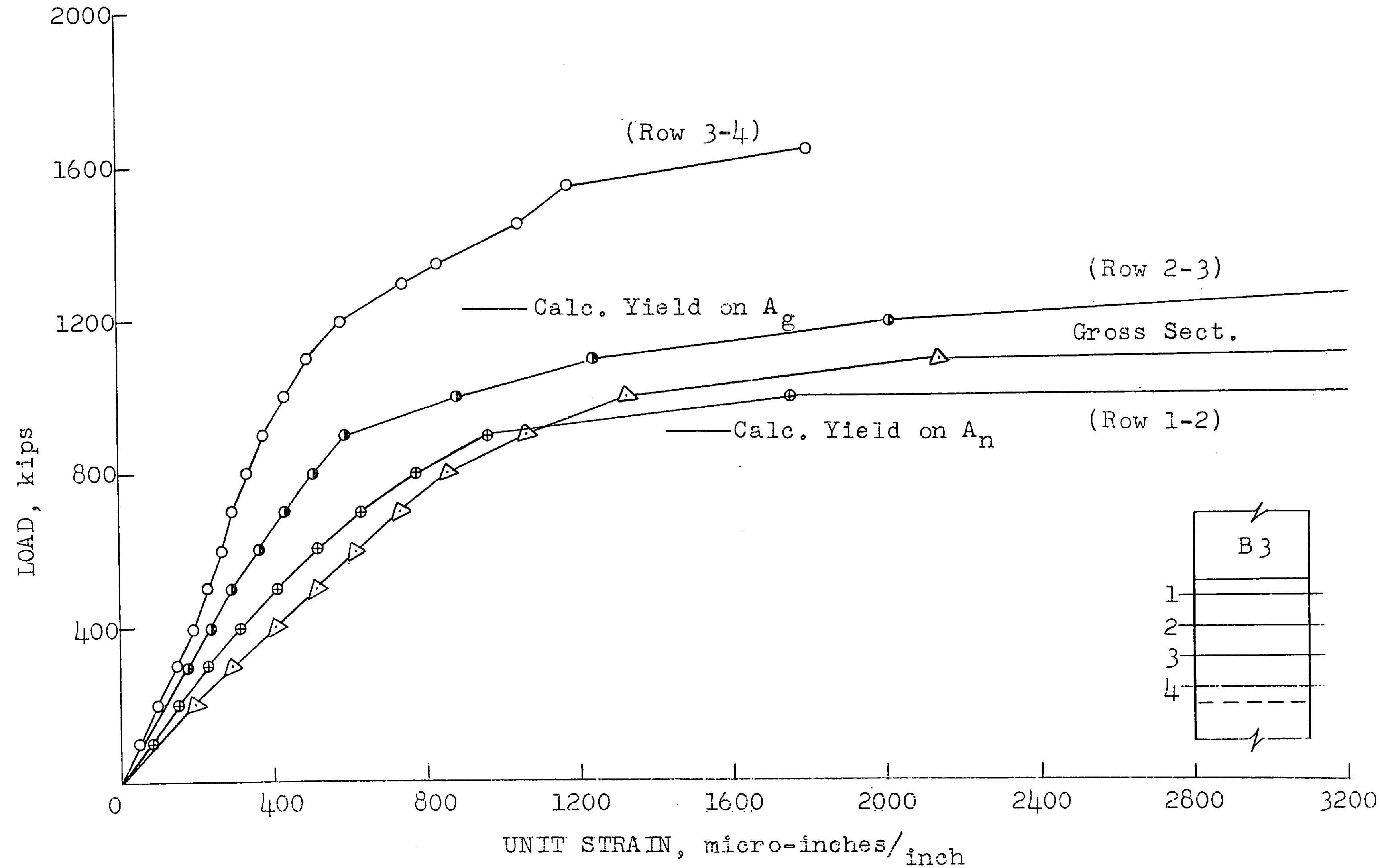


Fig. 29 LOAD vs STRAIN FOR MAIN PLATES OF JOINT B3

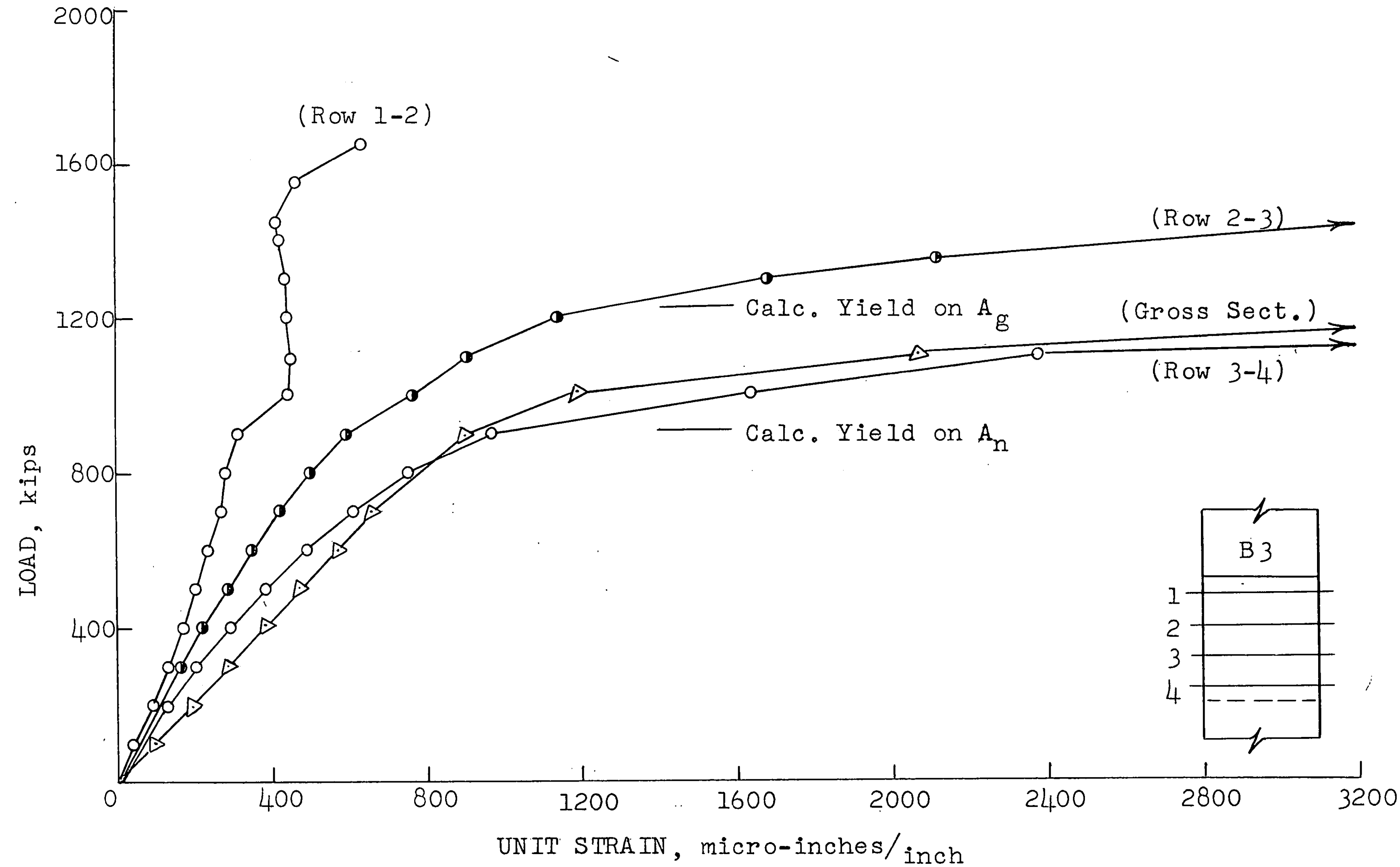


Fig. 30 LOAD vs STRAIN FOR WEST LAP PLATE OF JOINT B3

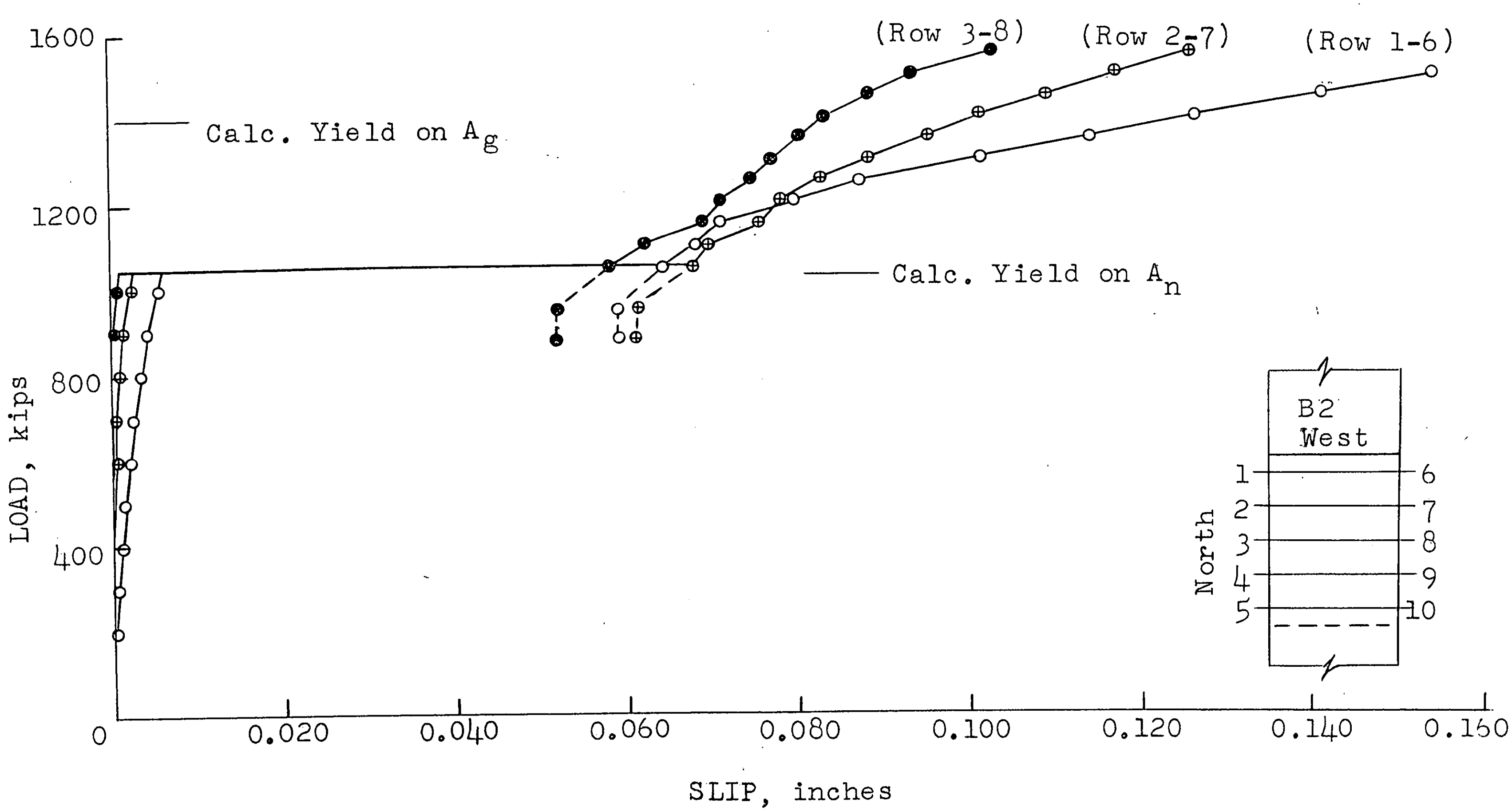


Fig. 31 LOAD vs SLIP FOR JOINT B2 - 25 7/8" A325 BOLTS

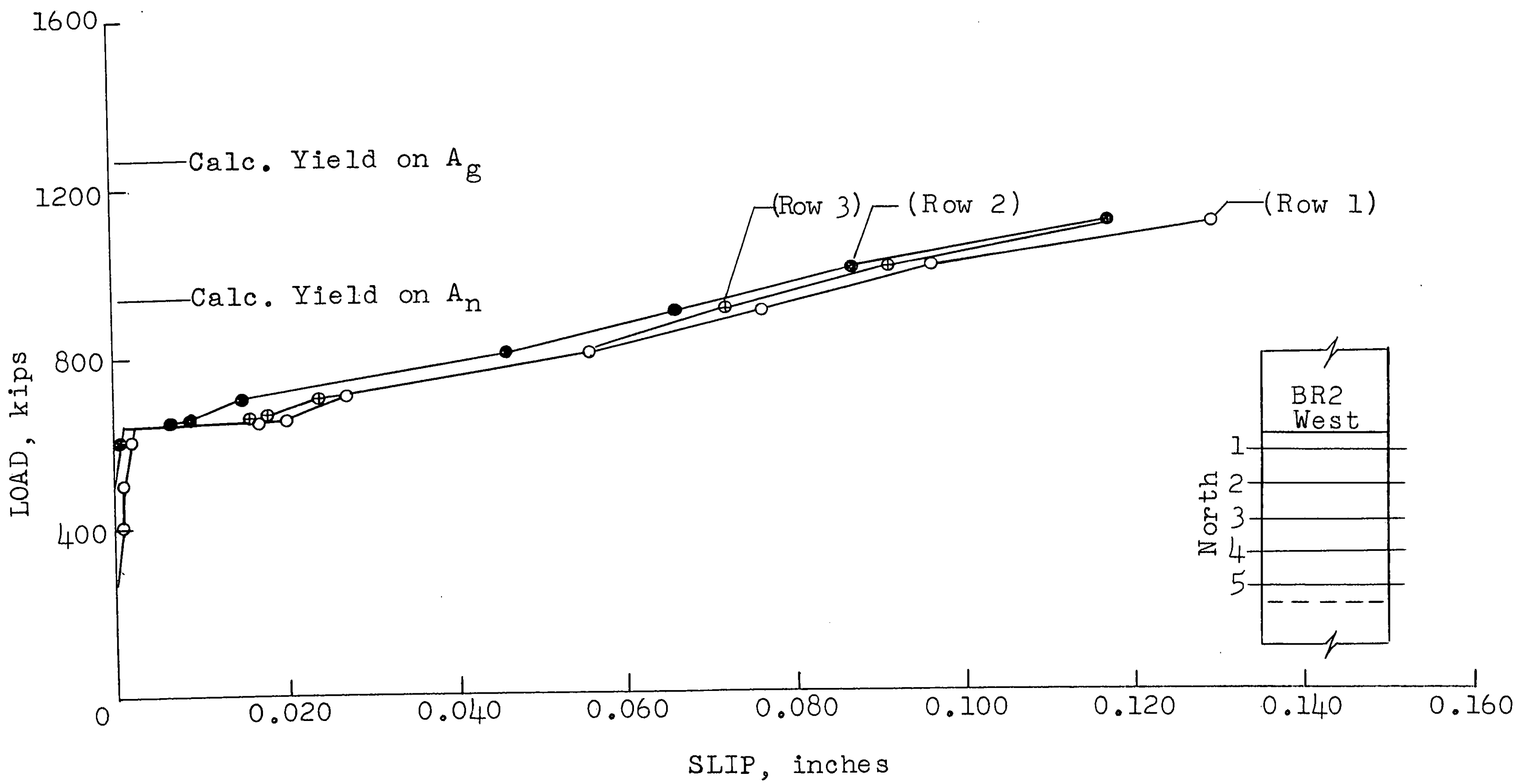


Fig. 32 LOAD vs SLIP FOR JOINT BR2 - 25 7/8" A141 RIVETS

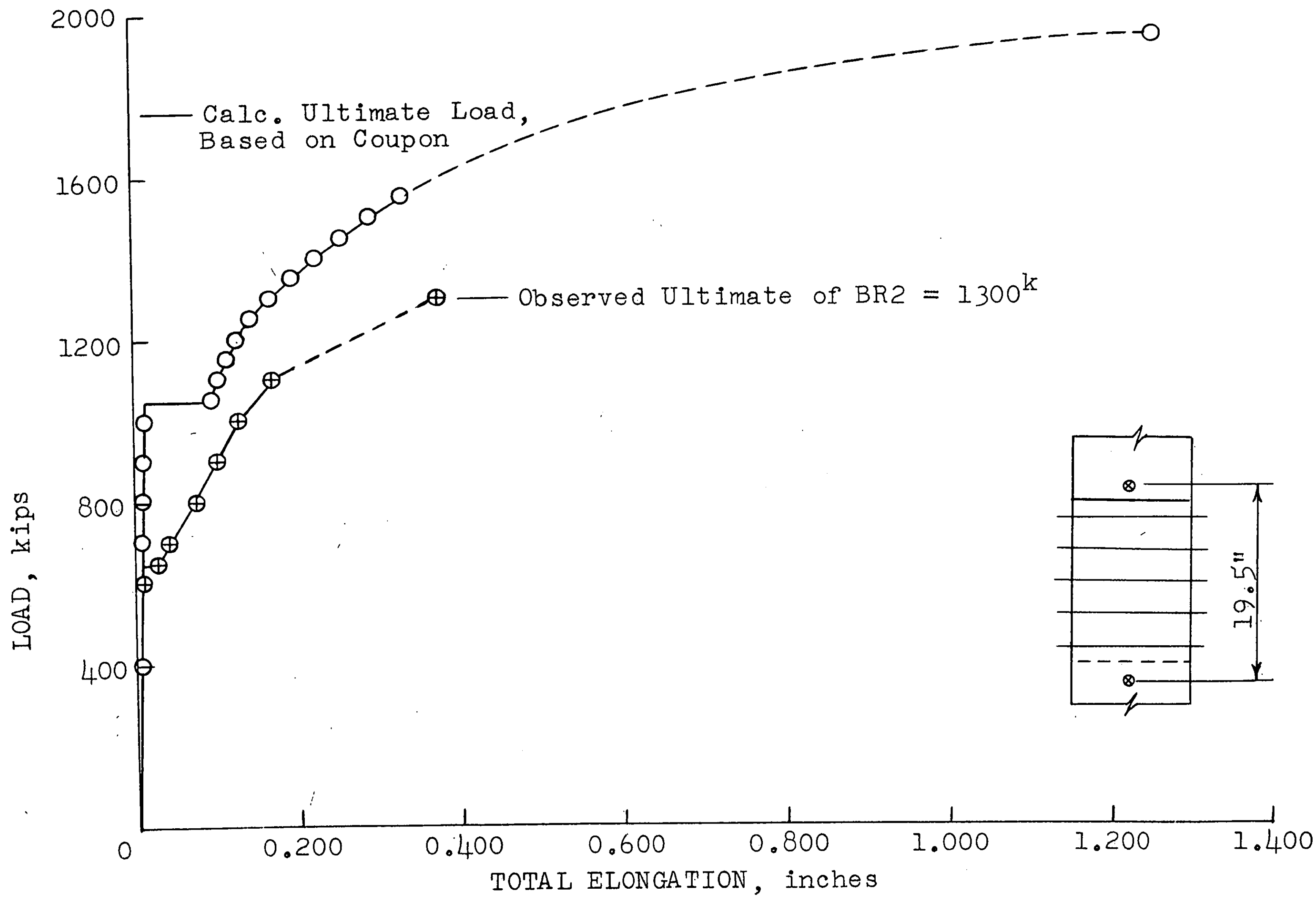


Fig. 33 LOAD vs TOTAL ELONGATION FOR JOINTS B2 AND BR2

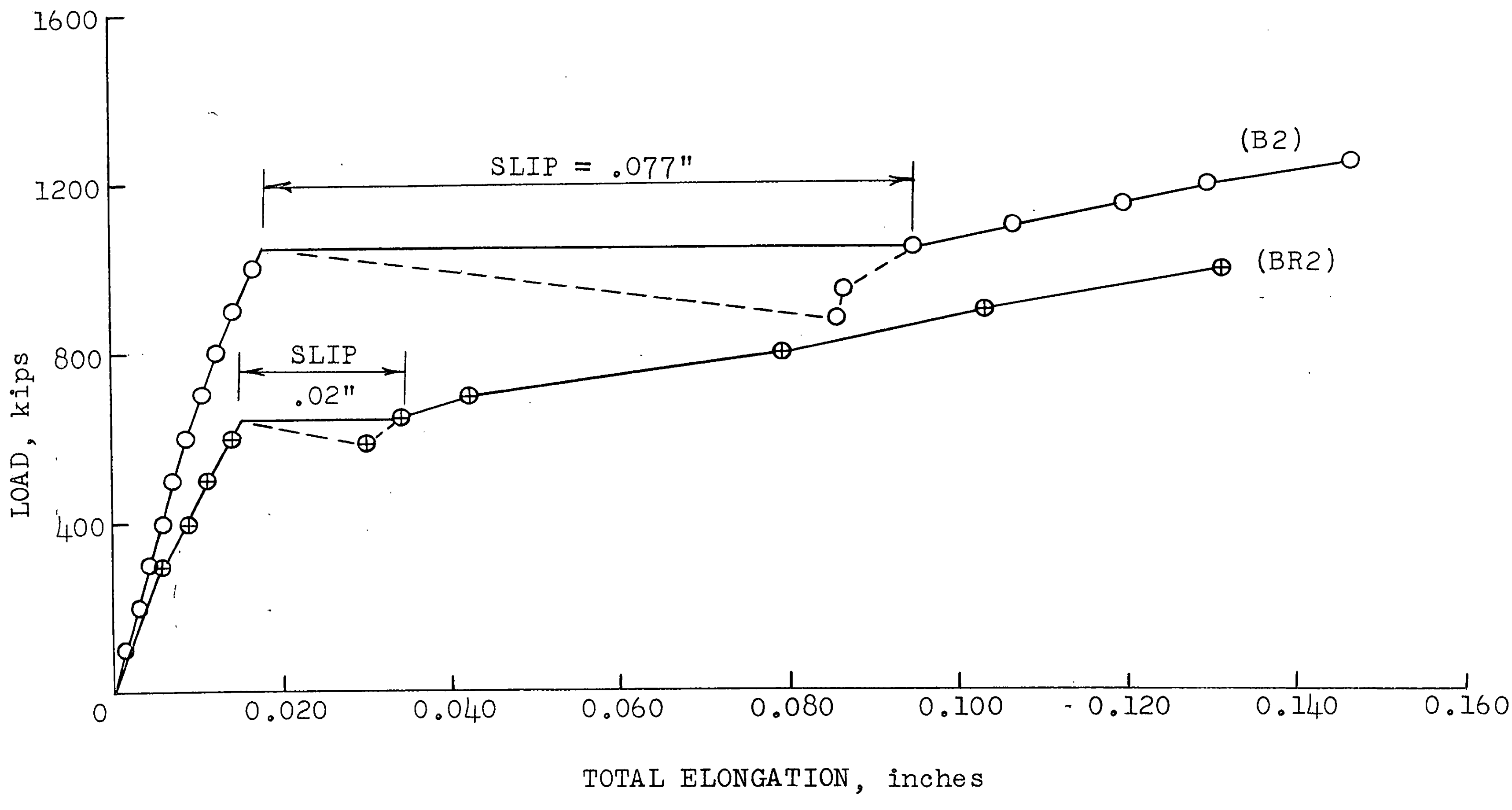


Fig. 34 LOAD vs TOTAL ELONGATION FOR JOINTS B2 AND BR2